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Evaluation of Procedures for Backcalculation of Airfield Pavement Moduli

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Final report

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Abstract

During the period October 2013 through August 2014, research was conducted at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, to improve the U.S. Air Force's (USAF's) airfield pavement structural evaluation procedures. Determining the structural integrity of airfield pavement relies on the analysis of pavement deflection data collected using the falling weight deflectometer (FWD) or heavy weight deflectometer (HWD). These deflection data are used to backcalculate pavement layer moduli, which are then used to determine the number of allowable passes and the allowable load that the pavement is able to support. The current airfield pavement analysis procedures, including the processes used for backcalculating layer moduli, were reviewed and compared to processes utilized by other transportation agencies and those proposed by academia. Airfield deflection data were then analyzed using current and proposed backcalculation procedures to provide recommendations for improving both the software and processes used by the USAF in evaluating the structural capacity of airfield pavement assets. This report summarizes the literature review, presents analyses of FWD/HWD data, and provides recommendations for improving the procedures used for backcalculation.

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Preface

This study was conducted for the U.S. Air Force Civil Engineer Center (AFCEC) under the project “Updated Backcalculation Procedures.” The Air Force’s technical monitor was Dr. Craig Rutland, AFCEC. The ERDC’s technical monitor was Jeb S. Tingle.

The work was performed by the Airfields and Pavements Branch (APB) of the Engineering Systems and Materials Division (ESMD), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Dr. Gary L. Anderton was Chief, APB; Dr. Larry N. Lynch was Chief, ESMD; and Jeb S. Tingle was the Acting Technical Director for Force Projection and Maneuver Support. The Acting Deputy Director of ERDC-GSL was Dr. Will McMahon, and the Acting Director was Dr. William P. Grogan.

LTC John T. Tucker III was the Acting Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
Inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
tons (force)	8,896.443	newtons

1 Introduction

Because the U.S. Air Force (USAF) mission depends heavily upon its airfield infrastructure, it has made large research investments over the past 40 years to develop pavement design and structural evaluation criteria, procedures, and software to ensure that its airfield pavements can support mission aircraft. As tire pressures and aircraft weights have increased steadily during this time, the design and evaluation software–Pavement-Transportation Computer Assisted Structural Engineering (PCASE) and evaluation equipment requirements have been updated for supporting new aircraft. However, a comprehensive review of the evaluation criteria, procedures, and software compared to those developed and used in the international pavements research community has not occurred in recent years.

In 2013, the USAF recognized the need to modernize these criteria and procedures and initiated a comprehensive research program utilizing pavement experts within the Department of Defense (DoD), private industry, and academia. The study presented in this report focuses on the backcalculation procedure and is the first of numerous research efforts to update the USAF's pavement evaluation process. Results from this study can also be applied to improve the pavement evaluation techniques for the other Services.

1.1 Definition, required inputs, and application of backcalculation

Backcalculation is the process by which measured pavement deflections are converted into pavement layer moduli. The conversion requires using an iterative process that applies a backwards approach to multilayer linear elastic theory.

In order to conduct backcalculation, the following inputs are required:

- Load and deflection data for each pavement section;
- Pavement layer thicknesses;
- General material information for each pavement layer including
  - Material type,
  - Reasonable modulus range, and
  - Poisson's ratio; and

- Computer program or spreadsheet to facilitate the backcalculation.

A number of backcalculation programs have been developed since the 1970s and are widely available. In general, these programs use numerical integration subroutines that calculate theoretical pavement deflections that attempt to match measured pavement deflections under simulated aircraft loads. The backcalculated moduli for the pavement layers are then used to determine the remaining life for the pavement in terms of remaining pavement life (passes-to-failure) or allowable gross aircraft loads and also to design pavement overlays.

1.2 Problem

While computer programs have made backcalculation a relatively fast process, continuous engineering judgment is required when evaluating even the simplest pavement system. Individuals with different levels of experience with backcalculation or knowledge about the particular pavement structure or location may attain different modulus results for the pavement layers despite starting with the same set of measured pavement surface deflections. This is due to the individual changing inputs or “fixing” values to obtain moduli more in line with their expectations and level of knowledge in the evaluation process and/or pavement structure. When executed by users with limited experience or knowledge, the risk of producing an erroneous or unrealistic evaluation assessment is high.

The issues related to the backcalculation process and, in turn, the pavement evaluation process, represent a major concern in the pavement evaluation community. Additional research is required to define an approach that provides reasonable moduli results that are mostly unbiased by the experience or knowledge of the user. Considering the multiple factors that are involved in the determination of the backcalculation results, a set of guidelines or recommendations to limit the variability in the backcalculation process must be defined.

1.3 Objectives and scope of the current investigation

The objective of the research presented in this report was to make recommendations to improve the USAF’s pavement analysis procedures for the backcalculation of airfield pavement layer moduli that produce both acceptable and objective backcalculated modulus results.

The specific objectives of this study were to

- Verify that reasonable pavement layer moduli results are provided by current backcalculation procedures compared to procedures and software used outside of the USAF and the DoD,
- Recommend improved backcalculation procedures for various pavement structures to include software modifications and/or inclusion of moduli reasonableness or screening approaches, and
- Provide a reference describing an improved backcalculation procedure for the USAF.

The scope of the research included

- Reviewing the current USAF backcalculation procedures and software,
- Reviewing backcalculation procedures and software used by the Army, transportation agencies, and those proposed by academia,
- Evaluating various backcalculation routines using HWD data collected during structural evaluations of military airfields,
- Evaluating screening approaches for backcalculated moduli to determine if the backcalculated moduli are reasonable, and
- Identifying recommendations to improve the USAF backcalculation procedures.

This report describes the current airfield pavement evaluation process used by the USAF and drawbacks and limitations of the current backcalculation process in Chapter 2. A review of alternative and complementary backcalculation procedures and software is presented in Chapter 3. Chapter 4 describes selected backcalculation software and pavement sections used for analysis purposes. Chapter 5 presents the analyses of the various backcalculation approaches. Chapter 6 presents results of structural evaluation, while pertinent conclusions and recommendations are noted in Chapter 7. An updated backcalculation and analysis procedure is provided in Appendix A.

1.4 Significance

Recommendations from this research will be used to help develop an overarching strategic plan for modernizing the military's pavement evaluation methods. Recommendations for improving the USAF's procedure may also be used for improving the processes used by the U.S. Army.

2 Current Airfield Evaluation Process

This chapter briefly describes the airfield pavement evaluation process used by the USAF and the drawbacks and limitations of the current backcalculation procedures used during the pavement evaluation process. The current USAF (DoD) evaluation procedure bases the remaining pavement life on the pavement thickness and the material properties of the pavement layers at the time of testing. The impacts of previous pavement loadings and environmental effects are not easily quantifiable, as field conditions and traffic applications are not normally tracked with time. Hence, these impacts are assumed to be represented by the backcalculated properties resulting from field tests at the time of evaluation. Furthermore, severe deterioration of the pavement's surface condition resulting from previous traffic loadings and environmental effects are taken into account when computing the allowable gross load if the pavement is considered to be in poor condition (i.e., having a pavement condition index [PCI] less than or equal to 40).

2.1 General objective of pavement evaluation

The objective of any pavement evaluation is to assess the pavement's strength and condition and to compute its load-carrying capacity (i.e., the remaining pavement life in terms of passes-to-failure and the allowable gross load). Unified Facilities Criteria (UFC) 3-260-03, *Airfield pavement evaluation,* provides the current military guidance for conducting airfield pavement evaluations (UFC 2001). USAF specific pavement evaluation guidance is provided in Engineering Technical Letter (ETL) 02-19 *Airfield pavement evaluation standards and procedures* (AFCESA 2002).

2.1.1 Pavement evaluation steps

In general, the following steps are used in airfield pavement evaluations:

1. Review of existing airfield design, construction, maintenance, traffic history, laboratory data, and weather records;
2. Designation of pavement facilities (runway, taxiway, apron) and subdivision of pavement into sections based on construction type, date, usage (Type A, B, C), and material properties;

3. Determination of the pavement surface condition using the PCI method in accordance with ASTM D 5340 (2012);
4. Determination of pavement layer characteristics including material thickness, type, quality, and strength. These data are used as inputs for structural evaluation; and
5. Determination of the load-carrying capacity (allowable gross load) and the pavement classification number (PCN) of the airfield pavements through the application of the evaluation criteria, using representative pavement properties.

The purpose of the study presented in this report was to improve the procedures for determining the structural capacity of airfield pavements. Therefore, Steps 4 and 5 were the primary focus of this investigation.

2.1.2 Pavement evaluation equipment

Step 4 in the pavement evaluation process is generally accomplished using nondestructive testing (NDT) methods, such as measuring pavement deflections with the falling weight deflectometer (FWD) or heavy weight deflectometer (HWD). The FWD simulates up to a 25,000-lb wheel load and is generally used to simulate truck or light aircraft traffic loads, and the HWD simulates up to a 50,000-lb wheel load representative of heavy aircraft loads. The HWD is the equipment used by the USAF for all non-contingency airfield pavement evaluations; it is also the primary equipment used by the Army for its airfield pavement evaluations.

For clarity, traditional airfield pavement evaluations are conducted at permanent airfield locations with pavements designed to support long-term mixed aircraft use. Contingency evaluations are conducted to determine if the airfield can support a short duration of limited aircraft traffic (typically C-17 or C-130).

The evaluation process may also be accomplished using destructive methods such as opening test pits, using semi-destructive methods such as a dynamic cone penetrometer (DCP), or using estimations of material properties based on material type. These last three methods may be required for contingency airfield pavement evaluations or for completion of a traditional pavement evaluation of infrastructure that has few records regarding its pavement structure and material properties.

Test pits are rarely utilized today because of the availability and acceptance of NDT methods by pavement evaluation personnel; however, DCP tests are still commonly used in both traditional and contingency airfield pavement evaluations. Evaluation of contingency airfields may be conducted in remote locations; and thus, the HWD may not be available for use due to deployability issues. Also, the DCP is a simple, easy-to-use device to quickly verify layer thicknesses and determine individual layer strengths.

While not required, the evaluation process is enhanced by taking pavement cores to confirm pavement thickness and to determine portland cement concrete (PCC) flexural strength (using splitting-tensile tests) and other material properties through laboratory tests. Coring may be required if the pavement has never been evaluated before. Another device, the portable seismic pavement analyzer (PSPA), is also used during traditional pavement evaluations to determine the pavement surface temperature for asphalt pavements (AC), material modulus, and flexural strength of PCC pavements.

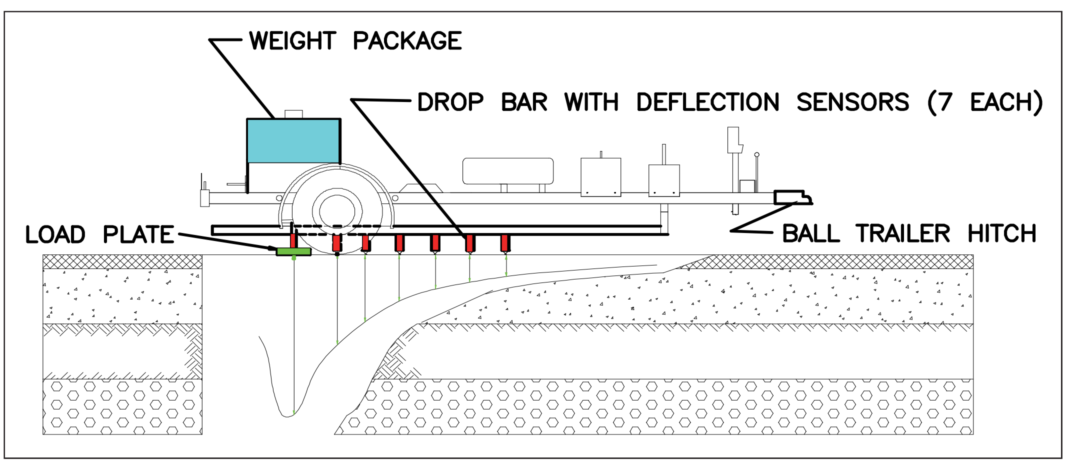
The Army uses a vehicle-mounted ground penetrating radar (GPR) system and a small ultrasonic pulse-echo device called the Mira to determine pavement layer thicknesses. GPR is primarily useful for determining the thickness of AC surface layers and thin PCC surface layers and may not be useful for determining thick PCC layers, such as those usually encountered on USAF airfields. The Mira is currently used for PCC surface thickness measurements. The USAF relies on coring the pavement for thickness determination in lieu of these devices; however, it has considered using the Mira in future evaluations.

Of these approaches, the U.S. military relies primarily upon NDT by using the HWD in lieu of the FWD because it has been shown to effectively simulate heavy aircraft loads. FWDs are, however, used for evaluating airfields that support lighter weight aircraft and for evaluating heliports. However, as mentioned in this section, data collected using the DCP, pavement cores, and PSPA are also used in the evaluation process. The data collection procedures including test locations, equipment requirements, and loading requirements are detailed in UFC 3-260-03 (2001). Brief descriptions of the equipment are presented in the following sections.

2.1.3 Heavy weight deflectometer (HWD)

The HWD is a nondestructive test device used to measure a pavement's response to applied, dynamic loading and simulates loads comparable to those generated by aircraft. The HWD produces an impulse load by dropping weights from different heights onto a plate of fixed diameter and is equipped with sensors (velocity transducers), spaced at different distances from the load plate (12-in. intervals), to measure the pavement's response (deflection) to the applied load. Figure 1 shows a schematic of the HWD loading configuration, the deflection basin, and a typical pavement structure. With the HWD, a force of over 50,000 lb may be generated by varying the drop height. In general there are four drop heights (represented by numbers 4, 3, 2, and 1) programmed into the HWD software that can produce approximate loads of 50,000, 35,000, 27,000, and 20,000 lb, respectively. The loads produced, however, depend on the number of weights used for testing, and the drop heights may be adjusted by the user, thus producing different load values. For the USAF, the standard drop heights are 2-4-4 for PCC and 1-2-2 for AC. The data collected are the peak deflections at each measurement location that define what is called a deflection basin. The deflection basin provides key parameters for evaluating the pavement strength and its ability to support traffic (Step 5). The basins are analyzed through backcalculation routines built into specific pavement models; for the USAF, this is WESDEF embedded in the PCASE software.

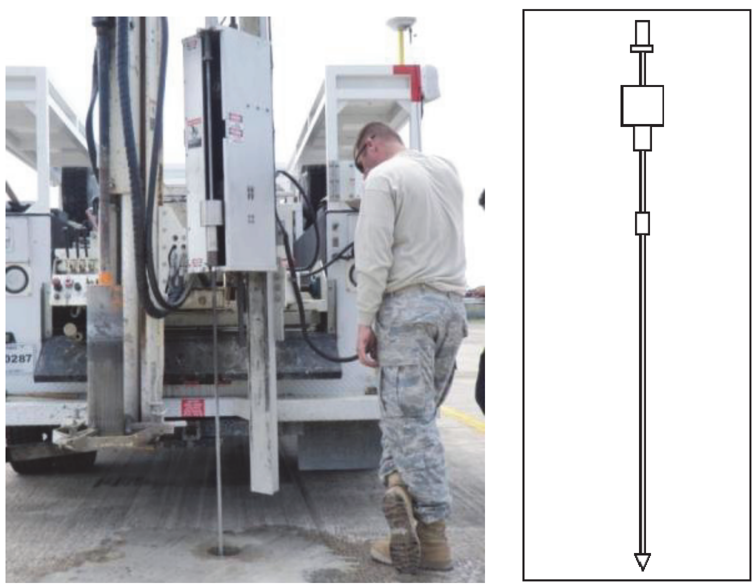
Figure 1. Schematic of the HWD.



2.1.4 Dynamic cone penetrometer (DCP)

The DCP is a hand-held portable penetrometer device designed to penetrate pavement layers to depths of between 26 and 50 in. with a 0.79-in.-diam cone. Testing with this device is conducted in accordance with ASTM Standard D6951-09, *Standard test method for the use of the dynamic cone penetrometer in shallow pavement applications* (ASTM International 2009). The cone is attached to a 0.625-in.-diam steel rod that is driven into the ground using either a 17.6- or 10.1-lb hammer that is raised and lowered by hand or mechanically for automated DCPs (Figure 2). The USAF uses both traditional and automated DCPs as part of its evaluation process. The device is used by measuring the penetration readings at selected drop intervals such as 1, 2, 5, 7, or 10 blows per reading with a minimum penetration of roughly 0.8 in. between recorded measurements.

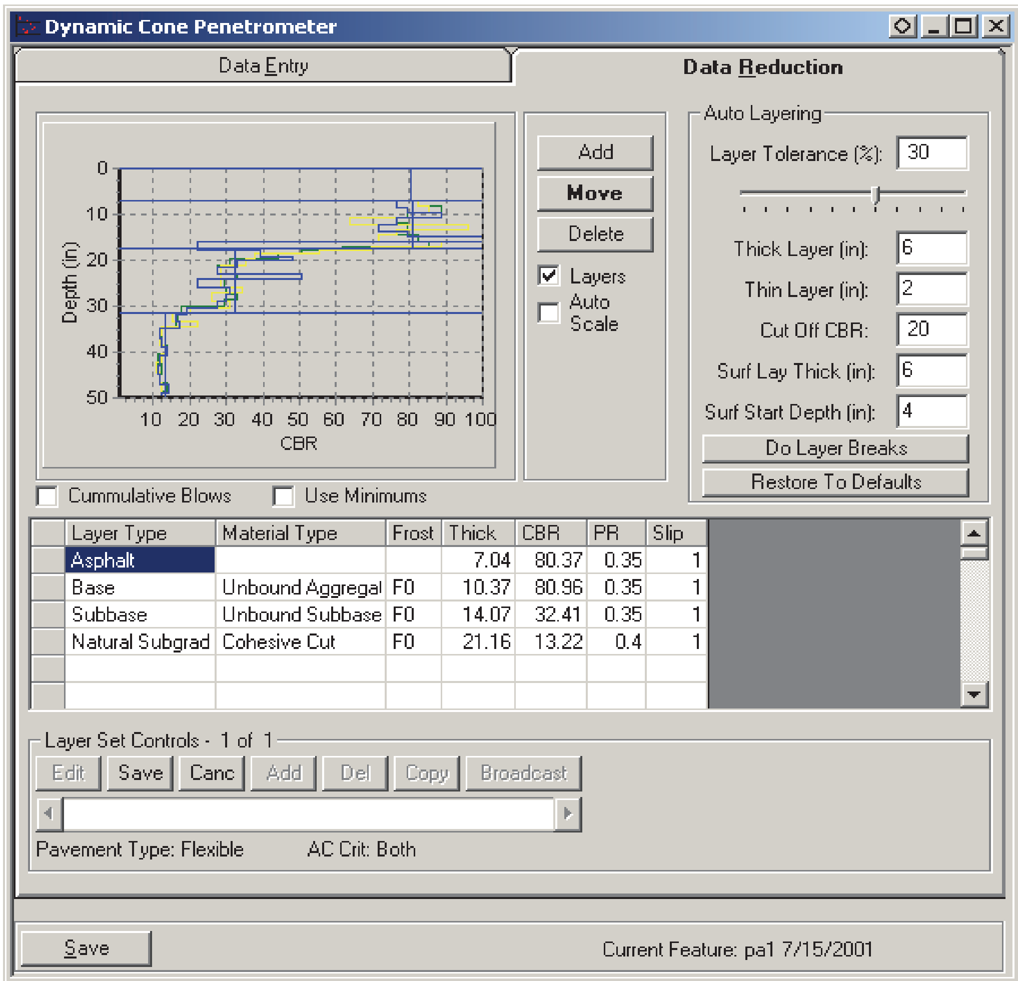
Figure 2. Automated DCP (left) and DCP schematic (right).



Once the test is completed, the drop intervals (blow counts) and corresponding penetration measurements are used to estimate the California bearing ratio (CBR), which is an empirical measure of strength. Cone penetration per hammer blow data are translated into a DCP index value (mm/blow). Equations have been developed to correlate this value to the CBR, and computer programs have been developed that allow the DCP data to be directly entered and stored for evaluation purposes. For example, PCASE has a DCP evaluation module in addition to its backcalculation routine and evaluation module. The equations generally adopted by most agencies and used in PCASE's DCP evaluation module are found in ASTM

D6951-09 (2009) and are based on those defined originally by the USACE. Changes in the CBR can be used to estimate the sublayer thicknesses by examining a plot of CBR with depth. The average CBR for each layer can then be used for evaluation purposes, as shown in Figure 3.

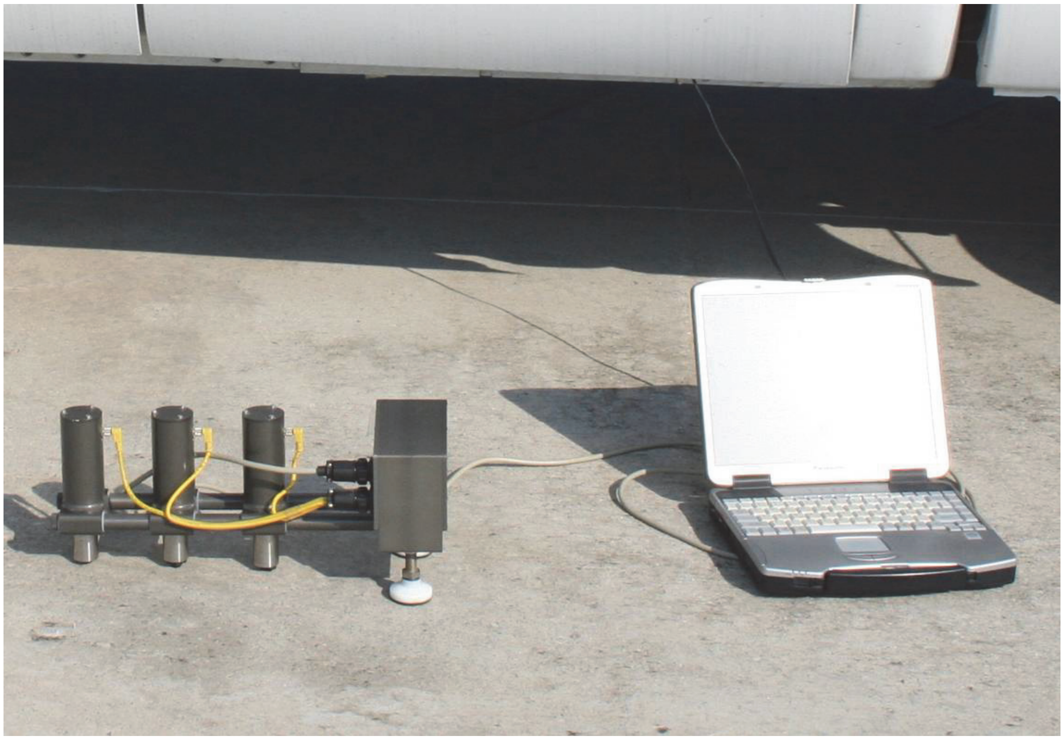
Figure 3. Using DCP data to determine layer thicknesses and CBR values in PCASE.



2.1.5 Portable seismic pavement analyzer (PSPA)

The PSPA (Figure 4) is a portable device that nondestructively evaluates PCC, AC, and prepared subgrade materials. The device consists of an electronics box, extension rods, a wave generation source, and two receivers. The system is controlled by a laptop computer, which also records the data. The PSPA generates ultrasonic surface waves (USW), the speeds of which are measured by the two receivers. The velocity of the USW, Poisson's ratio, and mass density of the tested material are used to calculate the modulus of the material. This device is also used to estimate the flexural strength of the PCC.

Figure 4. PSPA equipment and laptop.



2.1.6 Pavement core drill

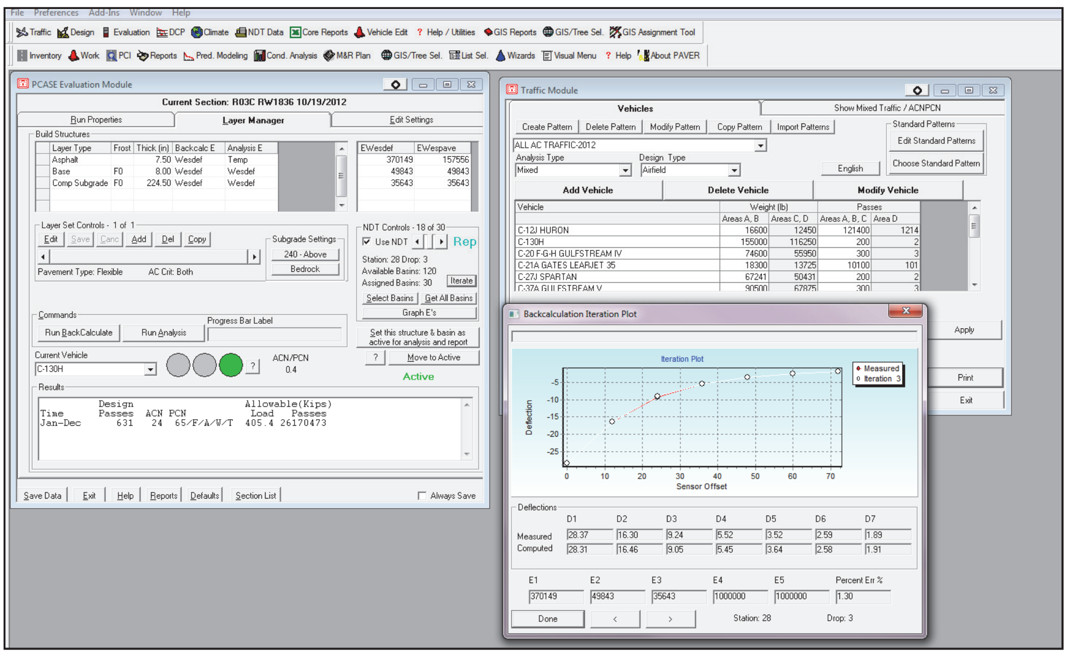
A pavement core drill is used to provide supplementary data to that collected with the HWD, DCP, and PSPA. Cores are taken during the evaluation process to confirm pavement thickness and to access underlying pavement layers for sampling or testing with other equipment, such as the DCP. Cores extracted from PCC pavements are also used to estimate pavement flexural strength using the splitting tensile test. Six-in.-diam cores are generally used by the USAF for both PCC and AC pavements, and the core drills are capable of coring to a depth of approximately 36 in. Figure 5 shows the core rig and splitting tensile test of a PCC core.

2.2 Pavement evaluation software

Step 5 in the pavement evaluation process for the U.S. military is accomplished using the *Evaluation Module* in the PCASE software (Figure 6) using the HWD deflection basins and other pavement materials data (i.e. thickness, flex strength, or modulus) collected in Step 4. The PCASE software incorporates the DoD criteria for designing and evaluating pavements (UFC 2001).

Figure 5. USAF core rig (left) and splitting tensile testing of PCC core (right).

Figure 6. PCASE software.



The *Evaluation Module* contains the routines for deflection basin backcalculation and for pavement analysis, which determines the pavement structural capacity in terms of aircraft allowable load and number of allowable passes. In PCASE, WESDEF is the embedded computer algorithm that contains the backcalculation routine. The pavement model implemented in WESDEF consists of a layered elastic system similar to other backcalculation computer programs used outside the DoD. The routine in WESDEF uses the HWD deflection basins and produces the elastic modulus of each pavement layer that provides the best fit between the computed and measured basins. The algorithm for determining the pavement structural capability in terms of allowable load and number of allowable passes is WESPAVE, which is also based on the layered elastic model and implements the failure criteria formula as described in the UFC 03-260-03 (2001).

The following section comprises a description of the backcalculation routine in PCASE, the implemented model, and the factors that induce changes in the output results. The section includes a description of the current utilization of the backcalculation procedure and pavement evaluation by the USAF.

2.2.1 The backcalculation routine: WESDEF

The backcalculation routine, WESDEF, uses the HWD measured deflection basins to estimate the pavement layers' moduli (E). Backcalculation is an iterative process in which the initial set of modulus values (seed values) for each pavement layer is assumed and is used to compute theoretical surface deflections that are then compared to the measured (HWD) surface deflections (deflection basin). The computed modulus values are adjusted, and the process is repeated until the best fit between the computed and the measured deflection basins is obtained (Figure 7). The basin computations are executed by applying the layered elastic model to the elastic modulus determined (or assigned) to each layer. In PCASE version 2.09, WES5 is the layered elastic model.

The inputs for WESDEF include the deflection raw data files from the HWD testing and the pavement layer structure (i.e., subgrade, base, and surface course) information. These raw data files contain information about the load applied during testing, deflection values, and sensor distance offset. The required pavement layer structure information includes the pavement's layer thicknesses, the layer Poisson's ratios, the interface conditions between layers, the seed modulus values, and a variability range of each layer's stiffness modulus. Table 1 shows the Poisson's ratio, seed modulus values, and minimum and maximum expected modulus values recommended in UFC 03-260-03 (2001) for each layer in the pavement structure in relation to the layer material and as entered into PCASE for an AC pavement in Figure 8.

Figure 7. Example of layered structure and deflections utilized in backcalculation.

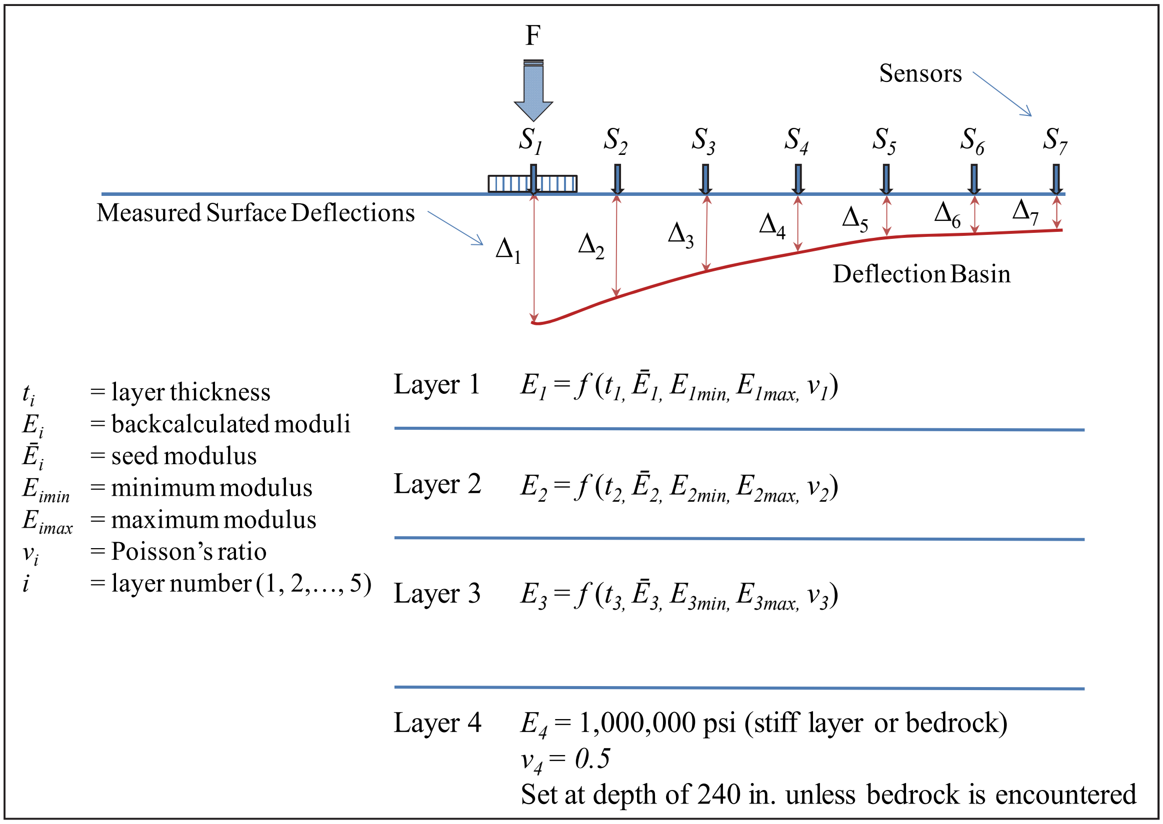
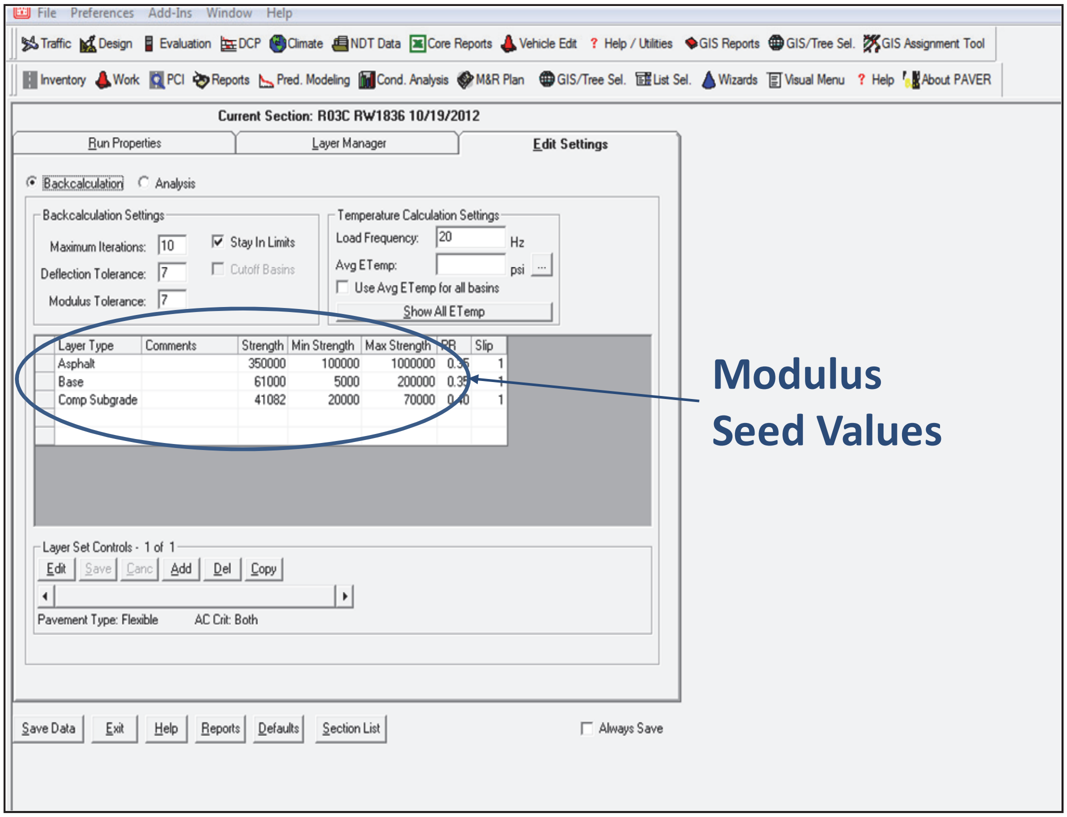


Table 1. WESDEF default modulus values and Poisson's ratios (UFC 03-260-03).

Material	Modulus range		Initial modulus estimate (seed value), psi	Poisson's ratio
	Minimum, psi	Maximum, psi		
Asphalt concrete	100,000	2,000,000	350,000	0.35
Portland cement concrete	2,500,000	7,000,000	3,500,000	0.15
Resin modified pavement*	700,000	3,000,000	1,700,000	0.27
High-quality stabilized base	500,000	2,500,000	1,000,000	0.20
Base-subbase, stabilized	100,000	1,000,000	300,000	0.25
Base-subbase, unstabilized	5,000	150,000	30,000	0.35
Subgrade	1,000	50,000	15,000	0.40

Note:*currently not included in WESDEF

Figure 8. Seed modulus values for backcalculation in PCASE.



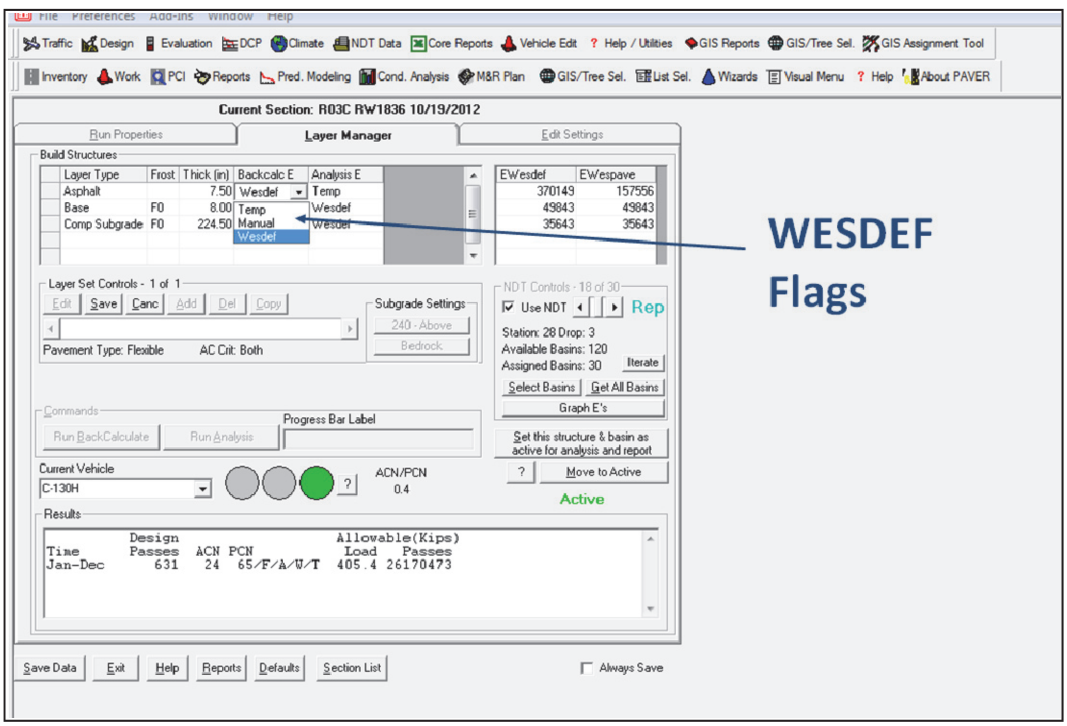
Prior to starting the backcalculation routine after importing the HWD files associated to each section under analysis, additional control features may be set in WESDEF. These control features, named “flags,” instruct WESDEF on how to process the layer moduli. During the iteration process, WESDEF adjusts each layer’s modulus value to the best fit for the computed basin and compares it to the measured deflection basin. However, in some cases, the moduli of selected layers can be set as a fixed value in relation to temperature at the time of testing, laboratory tests, or thickness of adjacent layers or depending on specific functions.

For base and subbase layers (granular layers) in a pavement structure, the WESDEF flags include “Manual” and “En+1.” The flag “Manual” indicates the modulus values are inserted manually and kept fixed during backcalculation. The flag “En+1” instructs the routine to compute the modulus in relation to the layer’s thickness and the modulus of the underlying layer. The equation expressing the relationship between layer thickness and modulus is contained in UFC 03-260-03 (2001). This flag is used when very low base or subbase moduli are predicted by WESDEF; however, other test results indicate strong moduli for these layers. This flag helps determine values more in line with those expected for strong base materials. For the subgrade material, only the flag “Manual” is allowed.

For rigid pavements, the flags associated with the layer corresponding to the PCC slab are “Manual,” which has the same function as previously described for the granular layers, and “Flex.” The flag “Flex” indicates that the concrete modulus is set at a value related to the concrete flexural strength (measured by using the PSPA or from flexural strength tests on core samples) and is kept constant during backcalculation.

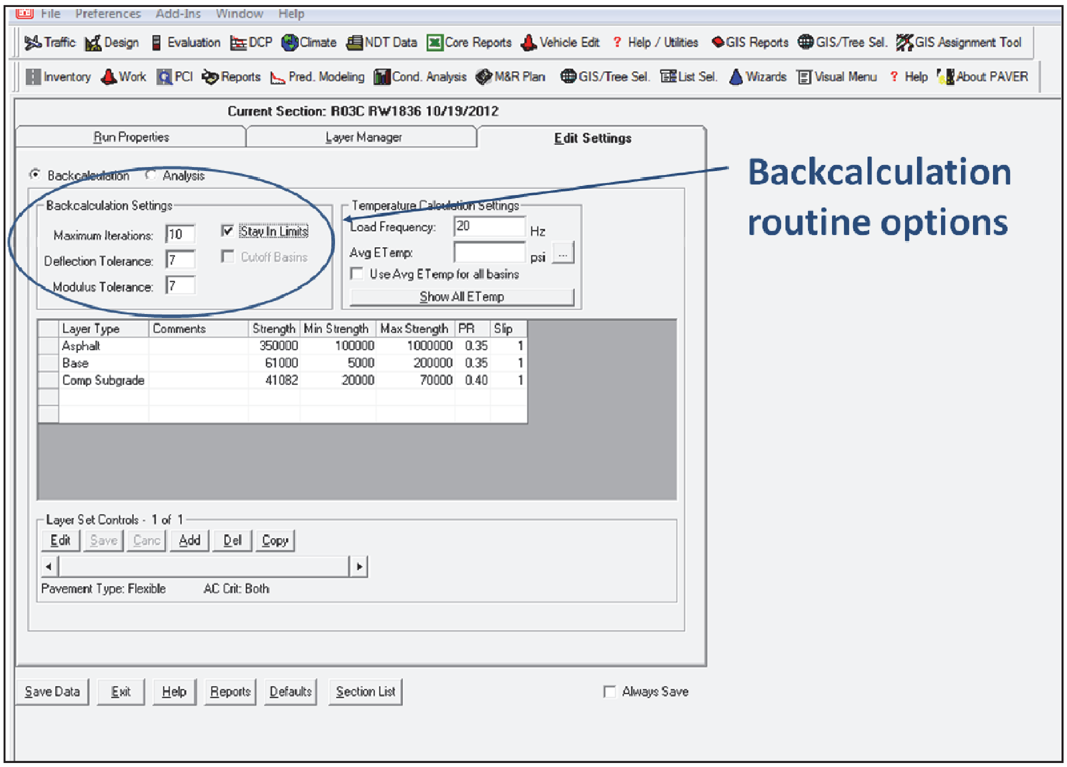
For flexible pavements, the flags for the layer corresponding to the AC layer are “Manual,” with the function as previously explained, and “Temp.” The flag “Temp” instructs the routine to fix the asphalt modulus value on the basis of the temperature at the time of testing. This modulus value is kept constant during backcalculation. Figure 9 shows the WESDEF flags for flexible pavement layers.

Figure 9. AC layer WESDEF flags in PCASE.



Additional settings for the backcalculation routine include the maximum number of iterations and the tolerances of the errors computed in terms of deflections and modulus values. The seed modulus values and the minimum and maximum values of each layer modulus can also be changed to attempt to improve the computed basin best fit. Furthermore, the software routine can determine modulus values outside the pre-set modulus range by turning off the **stay in limits** option. This option should be used with caution, as the backcalculated moduli can result in unrealistic values for the pavement layers. Figure 10 shows PCASE's setting options for backcalculation.

Figure 10. Backcalculation settings in PCASE.



Once all the backcalculation parameters and the required inputs are entered into PCASE, the backcalculation routine is activated by clicking **run backcalculate**. The backcalculation routine then seeks to find the layer moduli combination that best matches the measured deflection basin. Many deflection basins are input for each pavement feature collected at each pavement test location or station. The basin with the least total error across all the layers and basins is selected as the representative basin, as shown in Equation 1. The representative basin's moduli results are identified and used for analysis. This is different from other backcalculation software that report root mean square (RMS) error. The equation used in WESDEF for basin matching error is presented in Equation 2. Figure 11 shows an example of iteration and basin matching. Figure 12 shows example errors for various deflection basins (by station number). The flowchart in Figure 13 shows the iteration process followed in the backcalculation routine. It is important to point out that there is not a unique solution, regardless of the optimization scheme used. This is because the moduli results are influenced by the WESDEF input constraints (seed moduli, modulus range, etc.) and the limitations of the linear elastic model to represent the actual pavement.

Figure 11. Example of backcalculation iteration and basin matching.

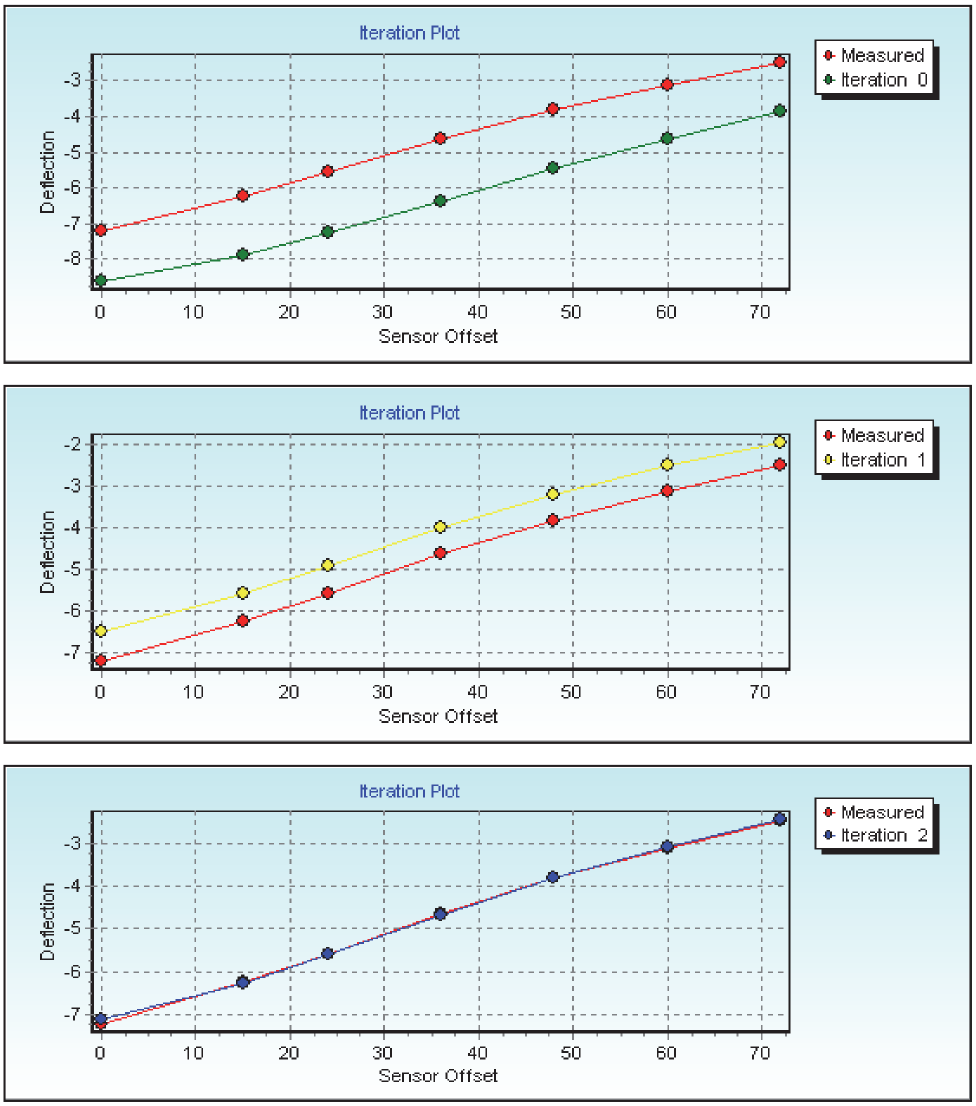
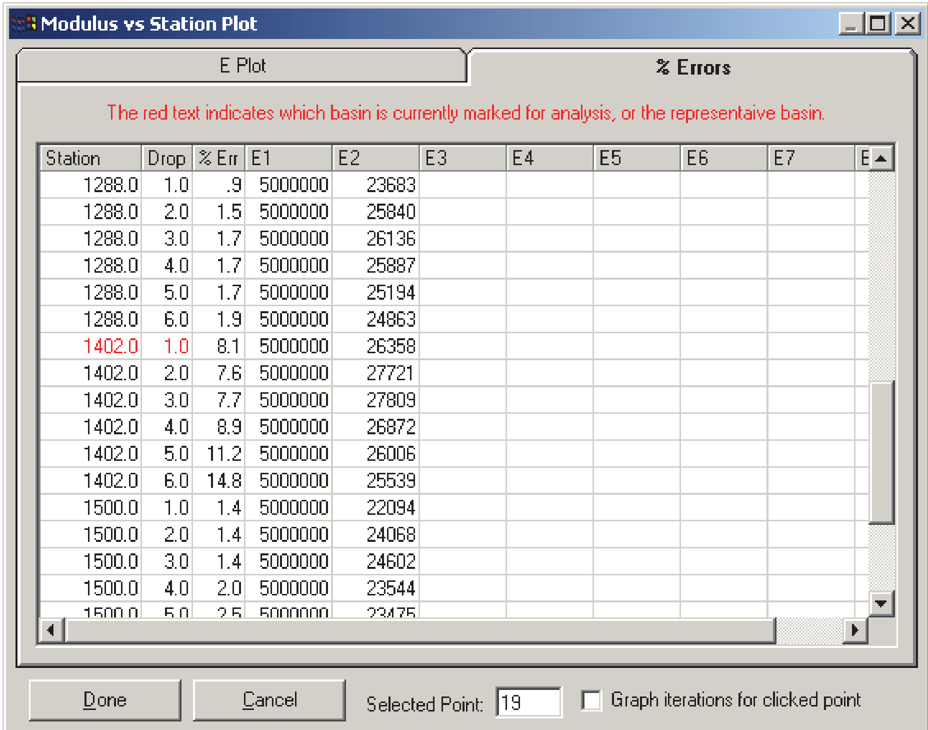
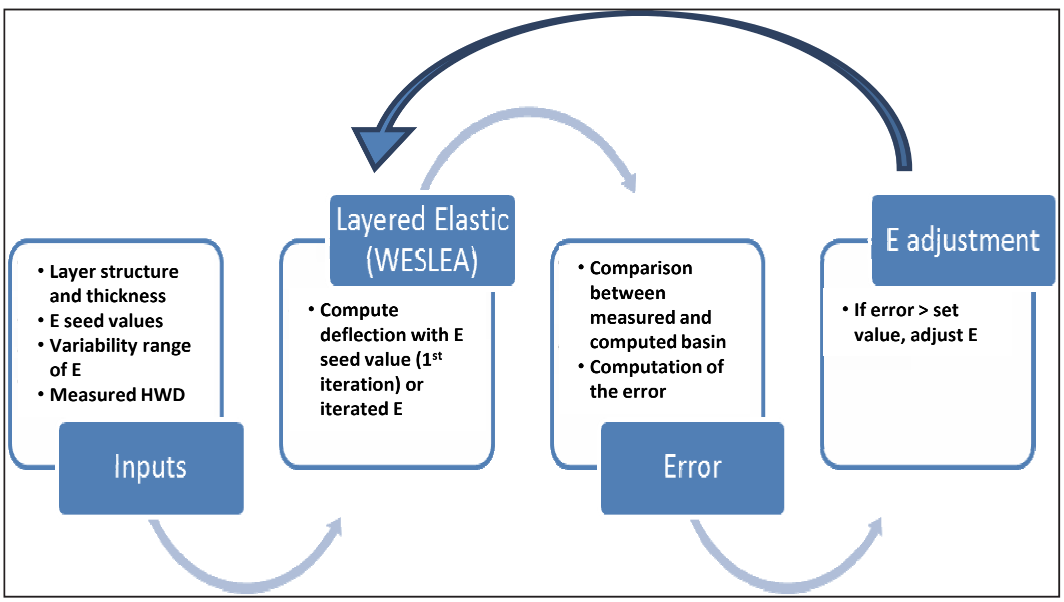


Figure 12. Example of error calculations.



Station	Drop	% Err	E1	E2	E3	E4	E5	E6	E7	E
1288.0	1.0	.9	5000000	23683						
1288.0	2.0	1.5	5000000	25840						
1288.0	3.0	1.7	5000000	26136						
1288.0	4.0	1.7	5000000	25887						
1288.0	5.0	1.7	5000000	25194						
1288.0	6.0	1.9	5000000	24863						
1402.0	1.0	8.1	5000000	26358						
1402.0	2.0	7.6	5000000	27721						
1402.0	3.0	7.7	5000000	27809						
1402.0	4.0	8.9	5000000	26872						
1402.0	5.0	11.2	5000000	26006						
1402.0	6.0	14.8	5000000	25539						
1500.0	1.0	1.4	5000000	22094						
1500.0	2.0	1.4	5000000	24068						
1500.0	3.0	1.4	5000000	24602						
1500.0	4.0	2.0	5000000	23544						
1500.0	5.0	2.5	5000000	23475						

Figure 13. Flowchart for the general backcalculation iterative process.



$$E_{error,k} = \sum_{i=1}^{NL} \left(\frac{\overline{E_i} - E_i}{\overline{E_i}} \right)^2 \tag{1}$$

where:

k = basin numbers

$\overline{E_i}$ = average modulus of the i^th layer among all the basins 1 to k

NL = number of pavement layers.

$$\%Err = \left[\frac{1}{n} \sum_{i=1}^{n} \left| \frac{z_{mi} - z_{ci}}{z_{mi}} \right| \right] \times 100 \qquad (2)$$

where:

z_{mi} = measured deflection at location of sensor i, mils

z_{ci} = calculated deflection at location of sensor i, mils

n = number of sensors.

2.2.2 Drawbacks to the backcalculation routine WESDEF

From a mathematical standpoint, the use of the WESDEF and other backcalculation routines is straightforward. The user inserts the layer types and thicknesses, modulus seed values and acceptable modulus range, and measured deflections. As mentioned previously, the user may also adjust the value of the error or the number of iterations influencing the definition of the moduli set. The backcalculation routine may produce acceptable results from a mathematical point of view (low errors); however, from the engineering standpoint, such results may not represent a realistic scenario of layer modulus values. Therefore, the mathematical result needs to be revised, accepted, or rejected based on the user's engineering judgment. As mentioned in Chapter 1, the user's knowledge and past experience with pavement evaluation is extremely important in determining the acceptance or validation of the results produced in the backcalculation routine.

2.3 Current backcalculation routine utilization

General guidance for WESDEF backcalculation is provided in UFC 3-260-03 (2001). Both the USAF and the U.S. Army follow this guidance but have developed additional recommendations and guidelines for backcalculation in an attempt to produce uniform backcalculation results among their pavement evaluation personnel. The Air Force has an internal document (provided by George VanSteenburg, Air Force Civil Engineer Center (AFCEC), April 2014) that is summarized in the following section but is generally shared during one-on-one training by experienced users with new personnel. The Army guidelines are not formalized into a document and are generally shared during one-on-one training by experienced users with new personnel.

2.3.1 USAF backcalculation recommendations and guidelines

Site-specific information recommendations include the following:

1. Personnel review the structural and PCI reports and evaluation data collected at the airfield during previous structural evaluations. This allows the engineers and/or technicians to become familiar with the features of the pavement and the characteristics of the pavement infrastructure.
2. Personnel obtain as-built drawings of construction executed after the last evaluation including overlay, rehabilitation, and maintenance efforts.
3. Personnel in-brief the installation prior to the pavement evaluation with the objectives of acquiring information regarding the installation's areas of concerns, discussing pavement utilization in terms of traffic, and possibly identifying causes of specific distresses. The discussion with the pavement users of how the pavement infrastructure is performing may provide useful information that can be utilized when assessing the backcalculation results.

In conjunction with site-specific information, the USAF follows these general guidelines when utilizing the backcalculation routine WESDEF in PCASE.

For PCC pavements, the guidelines are as follows:

- If pavement coring or DCP testing shows that the PCC slab is directly on the subgrade, evaluate the pavement structure as a two-layer system.

    - If pavement coring or DCP testing shows the existence of a base and/or subbase layers, configure the pavement structure as a three-layer system. If the base and subbase layers are of similar strength (based on DCP results or previous evaluation results) or are composed of similar material types, then combine them into a single base layer.
    - If the subbase and subgrade are of similar strength (based on DCP results or previous evaluation results) or are composed of similar

material types, then combine the subbase with the subgrade for backcalculation.

- For the first trial, backcalculate all layers with the modulus limits turned **on**. If results are erratic, unreasonable, or unacceptable from the engineering standpoint, turn **off** the modulus limit in the software routine and rerun the backcalculation routine.
- If erratic or unreasonable results are obtained for the base layer, then fix the base layer modulus based on known information. The layer base modulus can be computed utilizing DCP data and CBR information through the CBR–modulus relationship (or *k*–modulus relationship) (see UFC 3-260-03 for this relationship). Also in this case, trials can be done turning **on** and then **off** the backcalculation routine limits.

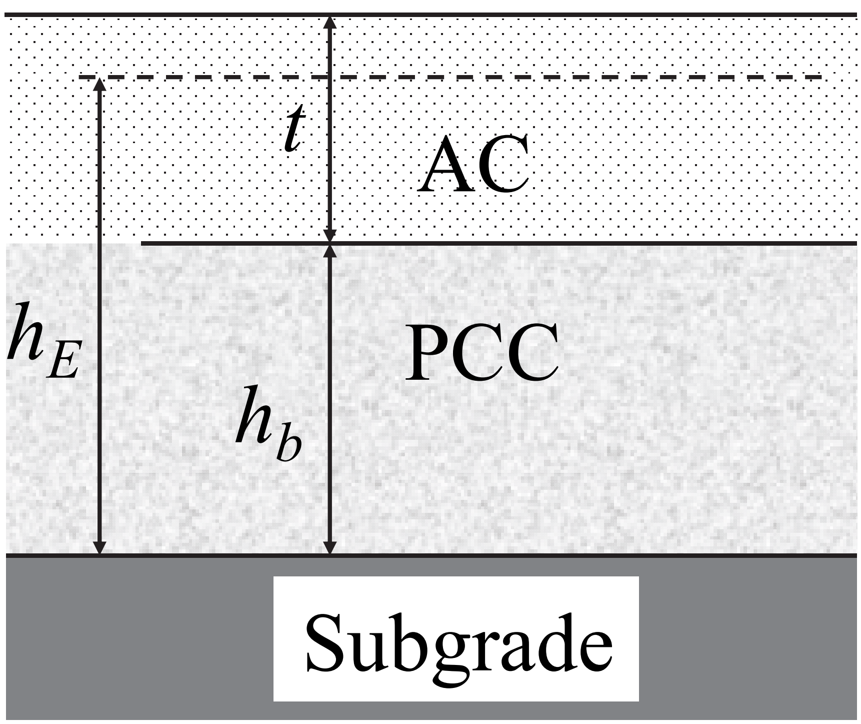
For AC pavements, the guidelines are as follows:

- Use a three-layer system (AC layer, base, and subgrade) as the first trial.
- Combine into one layer the base and subbase layers if the base and subbase layers are of similar strength (based on DCP results or previous evaluation results) or are composed of similar material types, or disregard a weak subbase if it is of similar strength to the subgrade based on DCP results or previous evaluation results.
- Backcalculate all layer moduli with the modulus limit turned **on** during the initial analysis. If results are erratic, unreasonable, or unacceptable from the engineering standpoint, turn **off** the modulus limits and rerun the backcalculation routine.
- If the routine produces erratic or unreasonable values for the base layer modulus, then fix the base layer modulus. The layer base modulus can be computed utilizing DCP data and CBR information through the CBR–modulus relationship. Also in this case, trials should be done turning **on** and then **off** the layer modulus limits.
- In case the backcalculation routine produces unacceptable values for a three-layer system, it is recommended to execute additional trials utilizing a four-layer system for the pavement structure. Also in this case, trials should be executed turning **on** or **off** the layer modulus limits and fixing the value of one or more layers based upon field data.

For composite pavements, the USAF guidelines are as follows:

- Use a three-layer system (AC layer, PCC base slab, and subgrade) as the first trial.
    - If the modulus value for the PCC layer is high (above 4,000,000 psi), keep the model.
    - If the errors are high, compute the AC and PCC layers as an equivalent thickness of PCC and conduct the backcalculation again. The concept and equation are presented in Figure 14.
- If the modulus values of the PCC layer are low (below 4,000,000 psi), indicating that the PCC slabs are extensively cracked or shattered, change the PCC base layer to a high-quality stabilized base, and rerun the backcalculation routine.
- If the AC layer is thinner than 3 in., transform the AC and PCC layers into a single PCC layer using the equivalent thickness equation. If the modulus values are very low (below 2,000,000 psi), consider repeating the analysis by setting the structure as a flexible layer over a stabilized or unstabilized base layer in lieu of a rigid base layer or high-quality stabilized base.

Figure 14. Equivalent thickness concept (UFC 3-360-03).



$$h_E = \frac{1}{F}(0.33t + C_b h_b)$$

where:

h_E = equivalent rigid thickness of combined overlay section (AC over PCC), in.
t = thickness of AC overlay, in.
h_b = thickness of the rigid base layer, in.
C_b = coefficient representing condition of rigid base typically ranges from 0.5 to 1.0, but the condition of the base slab is often not known. Use the following values in this situation:
C_b = 1.0 if there are no reflective distresses on the AC surface and the base pavement is positively in good condition
C_b = 0.8 if only reflective cracks or only joint reflective cracks are present on the AC
C_b = 0.5 if there are other reflective cracks in the AC in addition to the joint reflective cracks
F = factor controlling the degree of cracking in the rigid base (F=0.8 for contingency evaluations)

2.3.2 UFC 3-260-03 thin layer guidance

UFC 3-260-03 (2001) provides additional guidance for thin layers. It is not recommended that the modulus of layers less than 3 in. thick be computed, and the modulus of the thin layer should be fixed based on material type, temperature, etc., or else a thin layer should be combined with an adjacent layer to determine a composite modulus.

2.3.3 U.S. Army backcalculation recommendations and guidelines

The U.S. Army follows almost identical guidelines to those presented by the USAF and UFC 3-260-03 (2001) for evaluating its airfield pavements. However, there are three main differences:

1. During the first backcalculation analysis for AC, PCC, or composite pavements, the backcalculation is conducted within the modulus limits. If any limits are hit, then the backcalculation is conducted again with the limits turned **off**. The modulus ranges are then adjusted using the out-of-limit results until the backcalculation can be conducted without hitting any modulus limits. The subgrade moduli are typically adjusted first then the upper pavement layers if needed. Experience has shown that this approach minimizes error. If the results are reasonable, then they are accepted. If the

results are unreasonable, then DCP data for the base are examined (if available) or the moduli are fixed using engineering judgment.

2. For the evaluation of a composite pavement in which AC is placed over PCC and the AC surface is over 3 in. thick, the PCC base layer is set as a high-quality, stabilized base layer, and the moduli for each layer is computed. If the composite pavement has an AC layer less than 3 in., it is recommended that the modulus be fixed based on material type or temperature or that the pavement structure be set as a PCC pavement with no transformation of thickness.
3. If a macadam base is encountered, it is recommended that the base be set as a high-quality, stabilized base layer first. If results indicate that the macadam base is weak (hitting minimum moduli limits), then the pavement section is analyzed with the macadam as a stabilized or traditional base material. The base modulus can also be computed utilizing DCP data and CBR information through the CBR–modulus relationship and fixed to this value.

Despite these guidelines, the variability in selecting inputs and the other parameters still greatly affect the backcalculation of the pavement layer modulus values. Furthermore, the inclusion of field information may introduce additional issues related to the pavement model selected for representing the real scenario. Therefore, pavement evaluation represents a complex discipline significantly dependent on the experience and knowledge of the engineer in charge of the evaluation.

3 Review of Alternative or Complementary Backcalculation Procedures and Software

A number of publications were reviewed to identify backcalculation procedures, programs, and screening and/or quality checks used outside of the DOD. Comprehensive reviews of the history of backcalculation have been completed previously by Lytton (1989) and Ullidtz and Coetzee (1995) and are not repeated in this report. Several key publications addressing limitations to the backcalculation approach and suggestions for improving the process or for quality checks of moduli calculations are presented in this chapter.

3.1 Irwin (2002)

Irwin (2002) provides a summary of the general backcalculation routines, along with its fundamentals, limitations, and advantages. This paper expands upon the information provided by Lytton (1989) and Ullidtz and Coetzee (1995). Irwin (2002) concludes that backcalculation is a widely adopted approach because of three important advances in pavements theory and equipment:

1. Strong pavements have small deflections whereas weak pavements have large deflections when subjected to the same load. Therefore, pavement performance can be related to the deflection.
2. Mechanistic-empirical theories provide 'transfer functions relating deflections to stresses, strains, and overall pavement performance.
3. Pavement evaluation equipment (FWD/HWD) has been adequately developed to measure pavement surface deflections in response to load.

Irwin (2002) also explained the concept of surface modulus and its effect on the discrepancy between the pavement model and the real case scenario. He described the basic principle for which outer deflections can be used to determine the moduli of the deeper layers and the minimal effect of Poisson's ratio and its variability in the determination of the moduli through backcalculation. The author also explained elements that influence the backcalculation results— including errors affecting the FWD/HWD data, the presence of the bedrock, stress-dependent materials, and the pavement model itself (i.e., number of pavement layers).

Irwin (2002) also provides some recommendations and considerations in evaluating the validity of the backcalculated modulus; however, there are no objective and unique criteria to determine modulus validity and acceptability during the evaluation process. The first recommendation is to check the deflection basin fit. Since the main objective of the backcalculation routine is to determine the best set of modulus values that provides a deflection basin matching the measured basin, checking the RMS error represents one aspect in accepting the computed modulus values. An RMS error lower than 1 to 2 percent represents an optimal result, but it does not assure that the backcalculated modulus values are correct or representative from an engineering standpoint. Irwin (2002) provides these considerations for ensuring representative backcalculation moduli:

- There must be a good match between the assumptions in the model and in the backcalculation routine with the real pavement scenario.
- Testing in proximity of cracks or joints results in measured deflection basins that cannot be represented through an assumed model. The pavement conditions are not included in the model assumptions; therefore, the model will not provide realistic results.
- Deflection data have random and systematic errors.
- Setting the pavement model (number of layers and each layer's thickness) can be difficult, and in many cases subsurface layers are overlooked.
- Layer thickness is not uniform, and the material itself is not uniform along the area under analysis.
- Some layers are too thin to be well represented in the backcalculation routine. This is because of the mathematical process in the routine and because the combination of modulus and thickness has essentially no influence in the measured deflections or in the computed deflections under the designated model.
- Moisture content and bedrock depth may change along the pavement section under analysis.
- Temperature variations in AC pavements and slab size in PCC pavements influence the modulus because these variations affect the measured deflections. Slab size and pavement temperature have only recently become inputs for backcalculation.
- Most unbound pavement materials have stress-dependent behavior that is nonlinear, but most of the backcalculation models are based on linear elastic models. Therefore, this material peculiarity is not

included in the model assumptions and cannot be adequately represented in the model.

Irwin (2002) recommends that "the best way to overcome the problems and to assess the validity of the backcalculated moduli is to have a thorough knowledge of the materials in the pavement." Furthermore, Irwin suggests that rather than using the RMS error for assessing the validity of the modulus, the RMS error can be used to accept the validity of the model and to check to determine whether a different model may be more representative of the real pavement system. Irwin suggests that an RMS error over 4 percent indicates that the pavement model needs revision.

While Irwin's document does not provide any new methods for addressing limitations to the backcalculation approach or new procedures to determine moduli values or quality checks, it does provide a summary of the limitations of the backcalculation approach. It further highlights the issues presented in Chapter 2 of this report.

3.2 Pierce et al. (2010)

In a study commissioned by the Federal Highway Administration (FHWA), Applied Pavement Technology (APT), Inc. summarized the guidelines or instructions implemented by different state transportation agencies when utilizing backcalculation for evaluating pavement strength (Pierce et al. 2010). The researchers reached conclusions similar to those of Irwin's in regard to the factors affecting deflections, types of errors, material variability, and recommended modulus seed values in evaluating roads and highway pavements. Table 2 provides recommendations to solve some of the issues when backcalculating the moduli of pavement layers in flexible, rigid, or composite systems. Recommendations from this table are compared to current backcalculation recommendations for the DoD. Differences between DoD- and FHWA-recommended procedures are noted in this table in the "comment" column. Furthermore, this table provides recommendations that may be applicable for airfield pavement evaluations to overcome limitations in the WESDEF backcalculation software and process.

Table 2. Addressing specific conditions in pavement backcalculation analysis after Pierce et al. (2010).

Situation	Issue(s)	Recommendation(s)	Comment
AC Pavements			
Multiple bituminous lifts/layers	Many backcalculation programs limit the total number of layers to five including stiff layer (e.g., bedrock, saturated layer, water table). Typically, backcalculation programs are insensitive to differentiating moduli values between adjacent similar stiffness bituminous layers.	Combine adjacent bituminous lifts/layers. If total thickness is <3 in., assume a “fixed” modulus for the combined layer.	Similar to current DoD guidelines for using three- or four-layer models (plus rigid bottom layer). If the total thickness is <3 in., DoD suggests fixing the modulus of the thin AC layer based on temperature measurements at time of test.
More than 5 structural layers	Many backcalculation programs limit the total number of layers to five. As the number of layers increases, the error level may increase and result in an unreasonable solution.	Combine adjacent layers of similar materials or stiffness (e.g., bituminous layers, granular base, and subbase). Ideally, no more than four layers (surface, base, subgrade, and stiff layer, when applicable) should be modeled.	Similar to current DoD guidelines. Two- or three-layer systems (surface, base, and subgrade) are recommended. In WESDEF, the rigid layer is automatically added.
Thin surface layers (<3 in.)	Thin bituminous layers have minimal influence on the surface deflection. May result in unreasonable moduli for the thin bituminous layer. May result in a high error level.	Combine thin surface layer with adjacent bituminous layer(s). Assume a “fixed” modulus for the bituminous layer.	Similar to current DoD guidelines. Overlays are combined with the underlying AC layers for a single AC surface thickness.
Highly distressed surface (e.g., alligator cracking, stripping)	Highly distressed pavements violate the layered-elastic theory of homogeneity. Deflection basin may not produce the smooth basin predicted by layered-elastic theory.	Assume a “fixed” layer modulus for the bituminous layer. Consider using only the backcalculated results for the unbound layer moduli. Remove data points from analysis (condition should be well documented during testing).	***Currently not included in the DoD guidelines. This is a condition that should be noted in future evaluations.***
Bonding condition	Significant debonding/delamination of adjacent bituminous lifts/layers can result in unreasonable modulus values and higher error levels.	Confirm bond condition (coring) where delamination may be an issue. Assume a “fixed” layer modulus for the bituminous layer.	***Currently not included in the DoD guidelines. This is a condition that should be noted in future evaluations.***

Situation	Issue(s)	Recommendation(s)	Comment
Elevated testing temperatures	Bituminous layers are very sensitive to changes in temperature. On extremely hot days, the bituminous layer will have a significantly lower modulus. This may result in increased error levels.	Do not conduct deflection testing when pavement temperatures are above 90°F. Apply temperature correction factor for bituminous layer. Assume a "fixed" layer modulus for the bituminous layer.	*Currently not included in the DoD guidelines. This is a condition that should be noted in future evaluations if the evaluation situation allows. In contingency evaluations, these testing limitations may not be possible to follow.*
Saturated soils	In the backcalculation process, saturated soils can have an effect similar to that of a stiff layer.	If a saturated layer is known to exist, consider evaluating this layer as a stiff layer (see comments for a stiff layer).	*Currently not included in the DoD guidelines. This is a condition that should be noted in future evaluations. Determining whether the soils are saturated requires additional tests.*
Frozen subgrade	See discussion on presence of rigid layer.	Conduct deflection testing during unfrozen conditions. Include use of seasonal moduli in pavement design process.	Conducting NDT testing on frozen subgrades is not recommended in current DoD practice.
Nondecreasing layer stiffness with depth	Some backcalculation programs include a built-in assumption that layer moduli decrease with depth. Deflection of lower stiffness layer has minimal influence on deflection. Results in unreasonable moduli for the layer above the stiffer layer.	Confirm backcalculation program assumptions. Review results for reasonable moduli and RMS values. Assume "fixed" moduli for the bituminous layer.	Currently this is addressed in the guidelines for encountering PCC base slabs or macadam or stabilized base for backcalculation purposes.
Compacted/modified subgrade layers (sub-layering subgrade)	Treated materials often have higher moduli than the underlying subgrade. If unaccounted for this can result in unreasonable layer moduli and higher error levels.	For treated materials (e.g., lime- or cement-stabilized subgrade), consider as a base/subbase layer; may need to combine with base/subbase course if this results in more than three layers to analyze	General DoD practice is not to sublayer the subgrade. An option of using a compacted subgrade is used within PCASE.

Situation	Issue(s)	Recommendation(s)	Comment
Presence of stiff layer (e.g., bedrock, saturated layer, water table)	Stiff layers located at a shallow depth (< 40 ft) may result in unreasonable backcalculated moduli in the upper layers and higher error levels.	When possible, confirm location of bedrock, stiff layer, or shallow water table (borings, soil surveys). Conduct multiple backcalculation analyses that include the stiff layer at varying depths and stiffnesses.	Current DoD practice is to calculate depth to bedrock if testing indicates a stiff layer close to the surface (a subgrade modulus above 30,000 psi could indicate bedrock).
PCC Pavements			
Cement-treated or lean concrete base	Bonding condition between base and slab affects backcalculated modulus. AREA-based methods compute effective modulus of bound (stiffer) layers, and a layer ratio is used to determine individual layer moduli.	Review results for reasonable moduli. Conduct investigation to determine bonding conditions. Conduct materials testing to validate assumed layer ratio.	Current DoD recommendations are to set as a cement-stabilized base.
Presence of stiff layer (e.g., bedrock, saturated layer, water table)	A composite k-value is determined, which includes the influence of any stiff layer, if present.	Ensure the use of a compatible model in the design method.	Current DoD recommendations are to calculate depth to bedrock in PCASE.
Elevated testing temperatures	Curling of the slab may increase variability of backcalculated values. Joint load transfer efficiency values may be artificially high.	Conduct deflection testing when ambient air temperature is below 85 °F.	*No current DoD requirement for test temperature. This should be considered in the future, if possible. A single test temperature for both AC and PCC pavements is recommended in lieu of two different temperatures (90 or 85 °F, respectively).*
Small PCC slab sizes	Joint (or crack) discontinuity near the applied load influences results.	Review results for reasonable moduli. Assess impact of the use of slab size adjustments on reasonableness of moduli.	Current DoD practice does not take slab size into account for backcalculation. Deflection data are reviewed in the field to look for erroneous deflections that would be caused by a test conducted over a crack.
More than two structural layers	Procedure is limited to two structural layers and subgrade.	Combine adjacent layers of similar materials or stiffness.	Current DoD practice recommends a two-layer system.

Situation	Issue(s)	Recommendation(s)	Comment
Thin stabilized layer beneath PCC surface	Thin layer will have a minimal influence on the surface deflection. May result in unreasonable moduli for the thin stabilized layer. May result in a high error level.	Review results for reasonable moduli. Neglect the moduli of this layer and add thickness to the underlying layer.	***No current DoD guidance. This is a situation that needs to be addressed, and the recommendations presented should be considered.***
Composite Pavements			
More than two structural layers	Procedure is limited to two structural layers and subgrade.	Combine adjacent layers of similar materials or stiffness.	Currently, several different methods are used by the DoD to backcalculate composite layer moduli. These include setting the PCC base layer as a high-quality stabilized base (Army) or backcalculating all layers (USAF) as AC over PCC or converting the AC and PCC to an equivalent PCC thickness and evaluating the pavement as a rigid system.
Bonding condition	Significant debonding/delamination between HMA surface and underlying PCC pavement. Can result in unreasonable modulus values and higher error levels.	Confirm bond condition (coring) where debonding may be an issue. Model using appropriate bonding condition. Convert to equivalent thickness of PCC, assuming layers are unbonded.	Currently, the recommendation is to set the PCC as a high-quality stabilized base or to analyze the system as a PCC pavement if the AC thickness is less than 3 in. Converting the AC and PCC to an equivalent thickness is a recommendation that should be considered.
Small PCC slab size (e.g., thin whitetopping)	Joint (or crack) discontinuity near the applied load influences results.	Review results for reasonable moduli. Assess impact of the use of slab size adjustments on reasonableness of moduli.	***No current DoD guidance. This is a situation that needs to be addressed, and the recommendations presented should be considered.***

3.3 Stubstad et al. (2006a,b)

Stubstad et al. (2006a,b) present a different approach to using deflection data to determine the moduli of pavement layers: the forwardcalculation approach. Forwardcalculation, like backcalculation, uses the FWD/HWD deflection data; however, the forwardcalculation method utilizes closed-form formulas to generate a set of layer moduli instead of iterating various layered elastic moduli combinations to match the deflection basin. The main benefit of this method, as suggested by the authors, is that it does not rely on using engineering judgment to determine layer moduli, and there is only one solution for each layer moduli (not a combination of moduli that can offer the same deflections basin).

The forwardcalculation approach is based on the Hogg model (Hogg 1944), a hypothetical two-layer system consisting of a relatively thin plate on an elastic foundation. This model simplifies the typical multilayered elastic system into a two-layer system to calculate the in situ subgrade modulus of a pavement. In computing the subgrade modulus, the Hogg model utilizes the deflection measured under the center of the HWD load plate and the deflection at one of the offset sensors. Equation 3 calculates the Hogg subgrade modulus. Equation 4 is used to calculate the offset distance where the deflection is one half of the center deflection. Equations 5 and 6 are used to determine the characteristic length of the deflection basin. Equations 7 and 8 are used to calculate the theoretical point load stiffness/pavement stiffness ratio. Table 3 presents coefficients and different cases that may be considered using the Hogg model.

$$E_0 = I\frac{(1+\mu_0)(3-4\mu_0)}{2(1-\mu_0)}\left(\frac{S_0}{S}\right)\left(\frac{p}{\Delta_0 l}\right) \tag{3}$$

$$r_{50} = r\frac{(1/\alpha)^{1/\beta}-B}{\left[\frac{1}{\alpha}\left(\frac{\Delta_0}{\Delta_r}-1\right)\right]^{1/\beta}-B} \tag{4}$$

$$l = y_0\frac{r_{50}}{2}+\left[(y_0 r_{50})^2-4mar_{50}\right]^{0.5} \tag{5}$$

If $a/l<0.2$, then

$$l = (y_0 - 0.2m)r_{50} \tag{6}$$

$$\left(\frac{S_0}{S}\right) = 1 - \bar{m}\left(\frac{a}{l} - 0.2\right) \tag{7}$$

If $a/l<0.2$, then

$$\left(\frac{S_0}{S}\right) = 1 \tag{8}$$

where:

E_o = subgrade modulus, psi
μ_o = Poisson's ratio for the subgrade (0.4 for Case II)
S_o = theoretical point load stiffness, psi
S = pavement stiffness (p/Δ_o) (the area loading), psi
p = applied load, lb
Δ_o = deflection at the center of the load plate, mils
Δ_r = deflection at the offset distance r, mils
l = characteristic length of the deflection basin, in.
h = thickness of subgrade, in.
I = influence factor (see Table 3)
α = curve fitting coefficient (see Table 3)
β = curve fitting coefficient (see Table 3)
B = curve fitting coefficient (see Table 3)
y_o = characteristic length coefficient (see Table 3)
m = characteristic length coefficient (see Table 3)
a = radius of the load plate, in.
$\bar{m}$ = stiffness ratio coefficient (see Table 3)

Of the cases presented in Table 3, Case I is for an infinite foundation, while Cases II and III are for finite elastic layer foundation thicknesses with an effective thickness of 10*l* of the deflection basin. While three cases are presented, Case II is the recommended case for forwardcalculation.

To determine the composite modulus under the FWD load plate, the following equation is used based after the approach described by Ullidtz (1987).

$$E_c = 1.5 a \sigma_0 / d_0 \qquad (9)$$

where:

E_c = composite modulus of the entire pavement system under the load plate, psi
a = radius of the FWD load plate, in.
σ_o = peak pressure of FWD impact load under the load plate, psi
d_o = peak center FWD deflection reading, mils

Table 3. Hogg model coefficients (Stubstad et al. 2006a).

Equation	Coefficients		Case I	Case II	Case III
n/a	Depth to hard bottom	*h/l*	10	10	Infinite
n/a	Poisson's ratio	μ_o	0.50	0.40	All values
2	Influence factor	*I*	0.1614	0.1689	0.1925
3	Range Δ_r/Δ_o		>0.70	>0.43	All values
	$r_{50}=f(\Delta r/\Delta 0)$	α	0.4065	0.3804	0.3210
		β	1.6890	1.8246	1.7117
		B	0	0	0
	Range Δ_r/Δ_o		<0.70	<0.43	All values
	$r_{50}=f(\Delta r/\Delta 0)$	α	2.6947E-3	4.3795E-4	
		β	4.5663	4.9903	
		B	2	3	
4 & 5	$l=f(r_{50},a)$	y_o	0.642	0.603	0.527
		m	0.125	0.108	0.098
6 & 7	$(S/S_o)=f(a/l)$	$\overline{m}$	0.219	0.208	0.185

For the determination of the modulus of the bounded (upper) surface course, Stubstad et al. (2006a) applied the AREA approach introduced for rigid pavements by Hoffman and Thompson in 1981. The approach used for rigid pavements was modified for flexible pavements. The main difference in the formulas for determining the AREA (a deflection basin curvature index) term for rigid and flexible pavements was the number of deflection sensors used in the calculations. For rigid pavements, the AREA calculations use four deflection readings: the deflection under the load plate (D_o) and the next three sensors (D_{12}, D_{24}, and D_{36}), as shown in

Equation 10, while the flexible pavement calculations use only three (D_0, D_8, and D_{12}), as shown in Equation 11.

$$A_{36} = 6 * \left[1 + 2\left(\frac{d_{12}}{d_0}\right) + 2\left(\frac{d_{24}}{d_0}\right) + \left(\frac{d_{36}}{d_0}\right) \right] \tag{10}$$

$$A_{12} = 2 * \left[2 + 3\left(\frac{d_8}{d_0}\right) + \left(\frac{d_{12}}{d_0}\right) \right] \tag{11}$$

where:

A_{36} = AREA beneath the first 36 in. of the deflection basin
A_{12} = AREA beneath the first 12 in. of the deflection basin
d_0 = FWD deflection reading beneath the load plate, mils
d_8 = FWD deflection reading measured 8 in. from the load plate, mils
d_{12} = FWD deflection reading measured 12 in. from the load plate, mils
d_{24} = FWD deflection reading measured 24 in. from the load plate, mils
d_{36} = FWD deflection reading measured 36 in. from the load plate, mils

Equations to determine the surface modulus for both rigid and flexible pavements were then developed.

To calculate the modulus of the upper PCC layer,

$$E_{PCC} = \left[E_c * AF_{PCC} * k_3^{\frac{1}{AF_{PCC}}} \right] / k_3^{2.38} \tag{12}$$

where:

AF_{PCC} = AREA factor for PCC

$$AF_{PCC} = \left[(k_2 - 1) / \{ k_2 - (A_{36} / k_1 \} \right]^{1.79}$$

k_1 = 11.04 (the AREA where the stiffness of the concrete layer is the same as that of the lower layers)
k_2 = 3.262 (maximum possible improvement in AREA= 36/11.04)
k_3 = thickness ratio of upper layer thickness to load plate diameter

To calculate the modulus of the upper AC layer,

$$E_{AC} = \left[E_c * AF_{AC} * k_3^{\frac{1}{AF_{AC}}} \right] / k_3^2 \tag{13}$$

where:

AF_{AC} = AREA factor for AC: $AF_{AC} = [(k_2 - 1)/\{k_2 - (A_{12}/k_1\}]^{1.35}$
k_1 = 6.85 (the AREA where the stiffness of the asphalt layer is the same as that of the lower layers)
k_2 = 1.752 (maximum possible improvement in AREA= 12/6.85)
k_3 = thickness ratio of upper layer thickness to load plate diameter

Base layer or intermediate layer moduli (unbound- not stabilized) could be estimated through modular ratios for AC pavements:

$$E_{Base} = 0.86 * h_2^{0.45} * E_0 \tag{14}$$

where:

E_{base} = base modulus, psi
h_2 = base thickness (or intermediate layer), in.
E_0 = subgrade modulus, psi

For PCC pavements, the following equation is used to determine the moduli for the base layers in unbonded cases:

$$E_1 = \frac{h_1^3}{h_1^3 + \beta h_2^3} E_{pcc,app} \tag{15}$$

E_1 = modulus of the PCC layer, psi
β = E_2/E_1 (and shown in Table 4)
E_2 = modulus of the intermediate layer, psi

$E_{pcc,\,app}$ = apparent modulus of the PCC layer assuming no base course, psi

h_1 = PCC layer thickness, in.

h_2 = intermediate layer thickness, in.

Table 4. Ratios between concrete and base moduli provided by Stubstad et al. (2006b).

Base Type	β*= 1/β	Base Type	β*= 1/β
Continuously reinforced concrete pavement (CRCP)	1	Plant mix (cutback asphalt) material, cold-laid	20
Jointed plain concrete pavement (JPCP)	1	Plant mix (emulsified asphalt) material, cold-laid	20
Jointed reinforced concrete pavement (JRCP)	1	Cracked and seated PCC layer	25
PCC	1	Cement-treated soil	50
PCC (fiber reinforced)	1	Fine-grained soils: cement-treated soil	50
PCC (prestressed)	1	Sand asphalt	50
Lean concrete	2	Treated: portland cement	50
Econocrete	4	Bituminous-treated subgrade soil	100
Cement aggregate mixture	5	Fine-grained soils: lime-treated soil	100
Dense-graded, hot-laid, central plant mix AC	10	Lime-treated soil	100
Hot-mixed, hot-laid asphalt concrete (AC), dense-graded	10	Pozzolanic-aggregate mixture	100
Recycled AC, hot-laid, central plant mix	10	Recycled CRCP	100
Recycled AC, plant mix, hot-laid	10	Recycled JPCP	100
Soil cement	10	Recycled JRCP	100
AC	15	Recycled portland cement concrete	100
Dense-graded, cold-laid, central plant mix AC	15	Treatment: bitumen (includes all classes of bitumen and asphalt treatments)	100
Dense-graded, cold-laid, mixed-in-place AC	15	Treatment: lime, all classes of quick lime, and hydrated lime	100
Hot-mixed AC	15	Crushed rock	150
Hot-mixed, hot-laid AC, open-graded	15	Crushed stone	150
Open-graded, cold-laid, central plant mix AC	15	Treatment: lime and cement fly ash	150
Open-graded, cold-laid, mixed-in-place AC	15	Treatment: lime and fly ash	150
Open-graded, hot-laid, central plant mix AC	15	Crushed gravel	175

Base Type	β*= 1/β	Base Type	β*= 1/β
Recycled AC, cold-laid, central plant mix	15	Crushed slag	175
Recycled AC, cold-laid, mixed-in-place	15	Gravel, uncrushed	200
Recycled AC, heater scarification/recompaction	15	Sand	250
Recycled AC, mixed-in-place	15	Soil-aggregate mixture (predominantly coarse-grained)	250
Recycled AC, plant mix, cold-laid	15	Soil-aggregate mixture (predominantly fine-grained)	400

Table 4 presents modular ratios for the PCC to various base materials. Additional details of this approach may be found in Stubstad et al. (2006b). Spreadsheets based on these equations were developed and are available through the Long Term Pavement Performance (LTPP) Program sponsored by the FHWA.

Stubstad et al. (2006a,b) concluded that the overall approach works well for typical pavement materials and modular ratios when the underlying materials are not stabilized. The forward approach, however, is an empirical approach; and its best use is for approximating the stiffness of the upper (bound) layer in a pavement cross section or for quality control, comparative or routine testing, and analysis purposes.

The following are advantages of the forwardcalculation approach:

- The computations of the subgrade and surface course moduli are not dependent on each other or on other existing layer moduli.
- Forwardcalculation provides a unique solution and therefore can be considered a deterministic form and is not influenced by any type of engineering judgment in the determination or acceptance of the modulus results.
- Forwardcalculation produces approximate values that can be used for filtering or screening the values obtained through backcalculation.

However, there are some disadvantages:

- Two separate formulas are used for the modulus computations for base and subgrade; therefore, the two moduli may not be in accordance with

the center deflections and may not produce the same basin from which the moduli were derived.
- The surface course includes all the surface layers, and there is no method for distinguishing multiple layers or overlays.
- The determination of a third intermediate layer, if present, depends on the stiffness of the other two layers (surface layer and subgrade); therefore, trying to fit the center deflection may produce multiple intermediate-layer moduli lacking in uniqueness.

From the analysis, Stubstad et al. (2006a,b) concluded that

- The forwardcalculated modulus data should not be used to replace backcalculation or any other form of modulus of elasticity measurements.
- Forwardcalculation provides an estimation of the modulus on the pavement on site and is related to the specific measurements done with the FWD/HWD.
- The forwardcalculation approach is best used for screening purposes to evaluate whether backcalculated modulus values are reasonable.

Stubstad et al. (2006b) recommends computing both the forward- and backcalculated modulus values and comparing them to modulus ranges based on the material type listed in Table 5. If the calculated moduli are unrealistic, then they should be rejected. Then the ratio between the forward- and backcalculated modulus values should be checked against a reasonable range defined for the ratio shown in Table 6.

The availability of the spreadsheets to perform calculations simplifies the calculation process, and it was recommended that this approach be considered for screening backcalculation moduli, particularly for the subgrade materials. Details of these results are presented later in this report.

Table 5. Recommended moduli for pavement layers after Stubstad et al. (2006b).

Material	Minimum Modulus, psi	Maximum Modulus, psi
Base Materials		
Asphalt-treated mixture, nonpermeable asphalt-treated base	101,500	3,625,000
Gravel, uncrushed	7,250	108,750
Crushed stone	14,500	217,500
Crushed gravel	10,875	145,000
Sand	5,800	72,500
Soil-aggregate mixture (predominantly fine-grained)	7,250	101,500
Soil-aggregate mixture (predominantly coarse-grained)	8,700	116,000
Fine-grained soil or base	5,100	65,000
Hot-mixed AC	101,500	3,625,000
Sand asphalt	101,500	3,625,000
Dense-graded, cold-laid, central plant mix AC	101,500	3,625,000
Open-graded, hot-laid, central plant mix AC (PATB)	50,750	507,500
Cement aggregate mixture	290,000	2,900,000
Econocrete	507,500	5,075,000
Lean concrete	652,500	6,525,000
Open-graded, cold-laid, in-place mix AC	29,000	435,000
Limerock; caliche	21,750	217,500
Other—treated base	58,000	1,160,000
Surface Materials		
Concrete surface (uncracked)	1,450,000	10,150,000
AC surface	101,500	3,625,000
Unbound Subgrades		
Any unbound type	2,175	94,250

Table 6. Ratios used for comparisons between forward and backcalculated moduli (Stubstad et al. 2006b).

Description of the Correspondence Between the Forwardcalculated and the Backcalculated Modulus Values	Correspondence Codes	Ratio Between the Forwardcalculated and Backcalculated Modulus Values
Acceptable	0	2/3<Ratio≤1.5
Marginal	1	1/2<Ratio≤2 (and not code 0)
Questionable	2	1/3<Ratio≤3 (and not codes 0 or 1)
Unacceptable	3	Ratio≤1/3 or Ratio>3

3.4 Metha and Roque (2003)

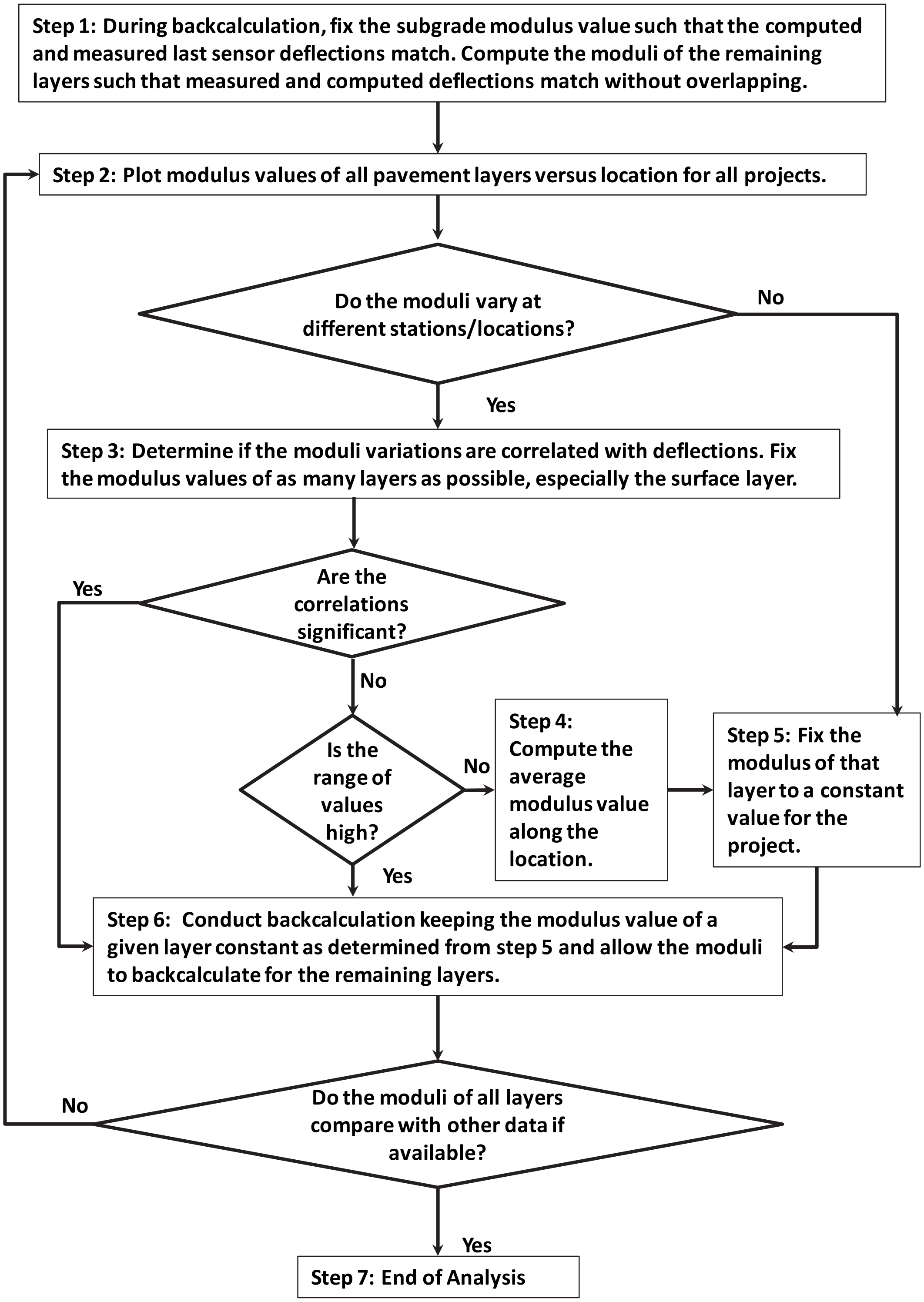
Metha and Roque (2003) proposed another approach (Figure 15) to utilize the FWD data to overcome the limitations of the backcalculation. The approach proposed by the authors included an investigation into the trend in the deflection spatial distribution over the entire tested area in determining the most reliable and appropriate solution of the backcalculation and evaluation process.

The authors also identified major drawbacks of the backcalculation routine similar to those reported by other researchers, including the dependency of the solution to the seed modulus values, the layered elastic model, and the material behavior that may be stress-softening or hardening. As other researchers concluded (i.e. Irwin 2002; Pierce et al. 2010), Metha and Roque (2003) pointed out that minimizing the error between computed and measured deflections does not necessarily provide accurate values of layer moduli or a set of moduli with a reasonable engineering meaning. Furthermore, the authors observed that better results were obtained in backcalculation when matching the curvature between measured and computed basins rather than each single deflection. The authors purport that the basin curvature can capture the pavement system stiffness and, therefore, the structural strength to an applied load.

Overall, the proposed approach was to address the variability of the modulus and the deflection along the entire section rather than concentrate exclusively on the accuracy of specific modulus values at a given location. Considering the variability in analyzing the FWD data, the specific modulus values were determined not to be as important as the changes in the structural characteristics along the entire section. For further investigation of the proposed approach, Metha and Roque (2003) included a step-by-step process. The general process is shown in Figure 15.

The Metha and Roque (2003) proposed approach is relatively easy and can be used with WESDEF. The procedure was recommended for consideration to determine whether less user judgment (and seed moduli manipulation) was required to determine reasonable layer moduli. Details of the results using this approach compared to traditional expert moduli calculations are presented later in this report.

Figure 15. Metha and Roque (2003) approach to backcalculation.



3.5 Horak and Emery (2009)

Besides the use of backcalculation, there are other approaches that utilize deflection-derived parameters for benchmarking or rating pavement conditions. One approach that has been applied to highway and airfield pavements is the benchmarking process proposed by Horak and Emery (2009). In this approach, a pavement layer rating is assigned based upon the variability of parameters defined by deflection measurements at specific FWD/HWD sensors without any modulus backcalculation. This information may represent a supporting tool in the validation process of assessing the validity of the backcalculated pavement layer moduli and overall complement the pavement evaluation.

Horak and Emery's approach is based on the subdivision of the deflection basin (referred to as the deflection bowl) in three zones. Figure 16 shows the typical distribution of these zones within a generic deflection basin. Zone 1 is close to the point of loading within a plate radius and no more than 12 in. from the point of loading, and the basin has positive curvature. This zone is used to determine the quality of the surface and base layers of a pavement. Zone 2 is included between 12 and 24 in. from the point of loading, and the basin curvature changes from positive to negative within this zone. This zone is examined to determine the quality of the subbase layer. Zone 3 is the furthest from the loading point, stretching from 24 to 72 in., and the basin has reversed (negative) curvature. This zone is examined to determine the quality of the subgrade.

In Horak and Emery's proposed benchmarking approach, the FWD sensor distribution consisted of nine sensors, located at distances of 0, 8, 12, 18, 24, 36, 48, 60, and 72 in. The deflection at each sensor is indicated as D_0, D_8, D_{12}, D_{18}, D_{24}, D_{36}, D_{48}, D_{60}, D_{72}, respectively. Table 7 summarizes the deflection-based parameters and the representative zones for these parameters. The range of variability for each of these parameters was evaluated in past research efforts, which indicated that for pavements where the layers are in good condition, the deflection parameter should have a specific range of variability (Table 8). Table 8 was developed for flexible roadway pavements and was redefined for benchmarking of flexible airfield pavements. Based on the range of variability of each parameter, it is then possible to rate the structural condition of the pavement layers and to identify structurally weak layers.

Figure 16.Curvature zones of a deflection basin (bowl) (from Horak and Emery 2009).

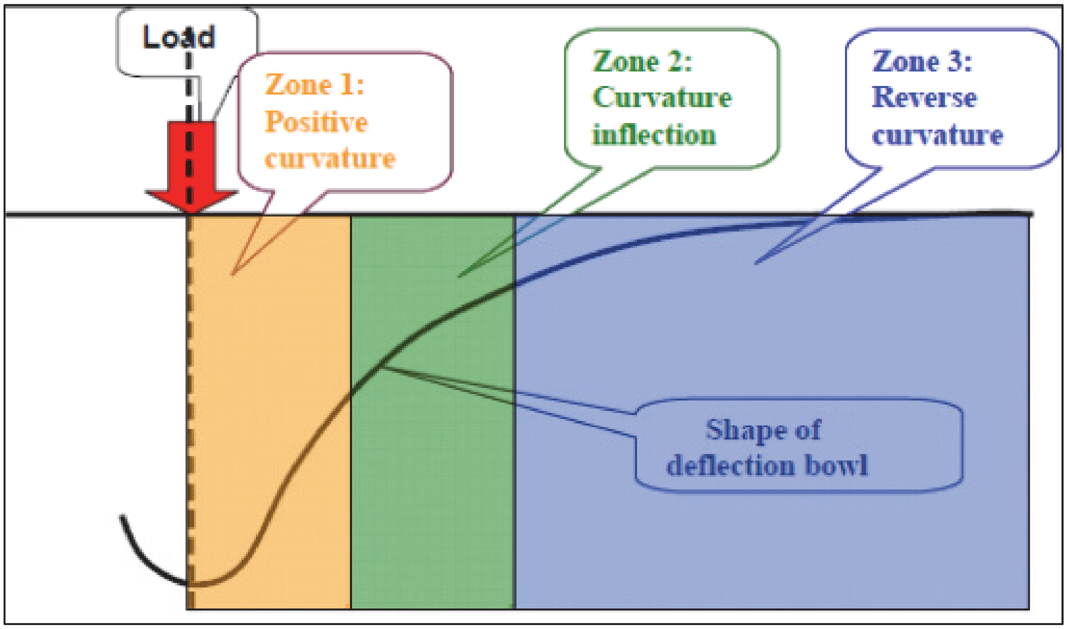


Table 7. Deflection-based parameters and zone correlation from Horak and Emery (2009).

Parameter	Formula	Zone
Maximum deflection	D_0 measured at the point of loading (center load plate)	1, 2, and 3
Radius of curvature (*RoC*)	$RoC = \left(\frac{L^2}{2D_0\left(1-\frac{D_8}{D_0}\right)}\right)$ where L=5 in. and 8 in. for the FWD	1
Base layer index (BLI) [indicated as SCI – surface curvature index]	BLI = D_0-D_{12} = SCI	1
Middle layer index (MLI) [indicated as BCI – base curvature index]	MLI = D_{12}-D_{24} = BCI	2
Lower layer index (LLI) [indicated as BDI – base damage index]	LLI = D_{24}-D_{36} = BDI	3

Note: (see Figure 16) for zone numbering.

Table 8. Deflection basin parameter structural condition rating criteria for various AC surfaced road pavement bases from Horak and Emery (2009).

Base Type	Structural condition rating	Deflection basin parameters				
		D0 (mils)	RoC (mils)	BLI (mils)	MLI (mils)	LLI (mils)
Granular base	Sound	<20	>4	<8	<4	<2
	Warning	20-30	2-4	8-16	4-8	2-4
	Severe	>30	<2	>16	>8	>4
Cementitious base	Sound	<8	>6	<4	<2	<2
	Warning	8-16	3-6	4-12	2-4	1.5-3
	Severe	>16	<3	>12	>4	>3
Bituminous base	Sound	<16	>10	<8	<4	<2
	Warning	16-24	4-10	8-16	4-6	2-3
	Severe	>24	<4	>16	>6	>3

The authors proposed two methods for providing realistic benchmarking values applicable to flexible airfield pavements:

1st method. The method is based on a generic correlation between aircraft loading and the normal 18-kip axle loading (for which Table 8 benchmarking values were developed). Experiences in South Africa on the combined analysis of airfield flexible pavements with various types of software concluded a conversion factor of about 1,000 E80 repetitions or equivalent single axle loads (ESALs) being equal to one pass of a B747-400. This approach is commonly used for airfields with low traffic volumes, with structures including granular base courses. Such structures are typical of South Africa and Australia. The benchmarks were adjusted from road situations, characterized by 82 psi of contact pressure, to airfield situations, characterized by 205 psi of contact pressure, and for a typical range of 3,000 remaining life passes of a Boeing 747-400. Table 9 proposes the adjusted values.

Table 9. Benchmark ranges for 205 psi contact stress on a granular base airport pavement (from Horak and Emery 2009).

Structural condition rating	Deflection basin parameters			
	D_0 (mils)	BLI (mils)	MLI (mils)	LLI (mils)
Sound	<75	<45	<25	<15
Warning	75-100	45-50	25-40	15-25
Severe	>100	>50	>40	>25

2nd method. This approach assumes linear elasticity regarding the contact stresses and the deflection basin parameters. The values in Table 8 are used to derive the benchmarking value in Table 10 using the linear elastic approach (model).

Table 10. Benchmark ranges for 250 psi contact stress on a granular base airport pavement (from Horak and Emery 2009).

Structural condition rating	Deflection basin parameters			
	D_0 (mils)	BLI (mils)	MLI (mils)	LLI (mils)
Sound	<60	<24	<12	<7
Warning	60-100	24-60	12-24	7-12
Severe	>100	>60	>24	>12

The authors showed two applications of their proposed benchmarking approach to existing airfields located in Australia and Namibia. The Australian airport had low traffic volume with infrequent Boeing 737 and 767 traffic. The use of the LLI, MLI, and BLI showed weakness at different types of layers constituting the pavement system at the subgrade level, at areas at the subbase/base or middle layer level, and at the base/surface level. The benchmarking approach also showed promising results in the Namibia airport. The approach revealed weaker areas in the surface and base layer of the pavements that would require rehabilitation of those layers/areas.

The benchmarking approach can be used as a screening process during a pavement evaluation program. One drawback is the benchmarks are established for flexible pavements only, and the currently proposed benchmarks are based on those derived for vehicles, not aircraft. Furthermore, there is no validation for U.S. airfields and climatic conditions using this approach.

3.6 Software and programs

Since the development of the FWD/HWD, a number of software packages have been developed to backcalculate layer moduli. The majority of the available software do not account for any plastic or visco-plastic behavior of the material constituting the pavement structure. Most backcalculation software use the iterative technique (as used in WESDEF), in which the program will repeatedly call upon a multilayer elastic subroutine to compute deflection basins by adjusting layer moduli with the objective to match the measured deflections. The iteration process stops when the difference between computed and measured deflections is lower than a set threshold, usually set by the user. Other techniques that have also been applied for backcalculation include the finite element method (FEM), the method of equivalent thickness (MET) (Ullidtz 1987), database, artificial neural network training, and genetic algorithms; however, the most commonly used technique is the iterative technique using linear elastic subroutines.

Pierce et al. (2010) summarized many of the currently available backcalculation software and programs. A partial list of software is shown in Table 11. Many programs were developed strictly for research purposes, while others are commercially available and used by various highway and airport agencies. As shown in the table, differences exist among programs, including convergence methods or schemes, number of allowable layers, analysis subroutine used, and applicable pavement types. Additional differences include considerations of nonlinear material behavior, variation of seed moduli inputs among programs, ability to modify or fix the seed moduli, variation in input parameters and assumptions, and depth to bedrock (Maestas and Mamlouk 1991). The abundant number of available programs has also led to a number of studies to compare predicted pavement layer moduli to determine the best backcalculation program. These include Kim and Nokes (1993), Ji et al. (2006), Ameri et al. (2009), Yin and Mrawira (2009), and Tarefder and Ahmed (2013), among many others. Problems associated with comparing programs include differences in the analysis routines leading to very different results as well as limitations on the inputs that may be controlled by the user to allow true comparisons of the backcalculated results. Even when executed by experts, it is impossible to know what the correct moduli are for the pavement sections evaluated unless laboratory tests are conducted. Even then, the laboratory moduli often do not agree with the backcalculated moduli.

Table 11. Partial list of backcalculation programs after Pierce et al. (2010).

Program Name	Publicly Available	Analysis Subroutine	Pavement Type	Maximum Number of Layers	Convergence Scheme	Error Weighting Function
BAKFAA	Yes	LEAF	Flexible/Rigid/Composite	10	Function root mean square error (RMSE)	Yes
BISDEF	No	BISAR	Flexible	Number of deflections; best for 3 unknowns	Sum of squares of absolute error	Yes

Program Name	Publicly Available	Analysis Subroutine	Pavement Type	Maximum Number of Layers	Convergence Scheme	Error Weighting Function
BOUSDEF 2.0	No	MET	Flexible	At least 4	Sum of percent errors	
CHEVDEF	Yes	CHEVRON	Flexible	Number of deflections; best for 3 unknowns	Sum of squares of absolute error	Yes
COMDEF	No	CHEVRON	Composite	3	Various	No
DBCONPAS	No	FEACONS	Rigid	2	N/A	N/A
DIPLOBACK	No	DIPLOMAT	Composite	3	Closed form solution	N/A
ELMOD6	No	Multiple: MET, WESLEA, FEM	Flexible/Rigid/Composite	Up to 5 including subgrade	Various	No
ELSDEF	No	ELSYM5	Flexible	Number of deflections; best for 3 unknowns	Sum of squares of absolute error	Yes
EMOD	No	CHEVRON	Flexible	3	Sum of relative squared error	No
Evercalc	Yes	CHEVRON	Flexible	3 (exclusive of rigid layer)	Sum of squares of absolute error	No
FPEDD1	No	ELSYM5	Flexible/Composite	3 or 4	Relative deflection error at sensors	No
ISSEM4	No	ELSYM5	Flexible	4	Relative deflection error	No
MICHBACK	Yes	CHEVRON	Flexible/Composite	3 + rigid layer	Least squares	Yes
MODTAG	Yes	CHEVLAY2	Flexible/Rigid/Composite	2 to 15 layers; maximum of 5 unknown layers	Relative deflection error at sensors	No
MODULUS 6.0	Yes	WESLEA	Flexible/Composite	4 + rigid layer	Sum of relative squared error	Yes
WESDEF (in PCASE	Yes	WES5	Rigid/Flexible/Composite	5	Sum of squares of absolute error	Yes
RPEDD1	No	ELSYM5	Rigid	3 or 4	Relative deflection error at sensors	No

Of the numerous programs available, few are applicable for flexible, rigid, and composite pavements. Additionally, not all programs can directly accommodate a composite pavement in which AC over PCC slabs is encountered. Some software programs require setting the PCC base layer as a stabilized base for backcalculation or adjusting the base moduli to higher seed moduli. This is a common practice in Army pavement evaluation using WESDEF, although a rigid layer may be also be used. Based upon review of the literature, broad use for airfield pavements, and their ability to be used for all pavement types, BAKFAA, ELMOD6, and WESDEF (in PCASE) were selected for additional investigation and are described in Chapter 4.

3.7 Summary

The literature review on the current status and use of the backcalculation procedures outside the DoD confirmed the complexity of the discipline that has been considered by many as an art rather than a deterministic and objective process. The analyses of the current backcalculation procedure, its utilization, and the literature reveal several issues with the process. The literature also reveals additional methods that can be potentially applied to improve backcalculation procedures and additional software programs used outside the DoD. One of the issues identified is the uniqueness and objectivity of the solution reached through backcalculation and, therefore, the consequent pavement evaluation.

The solution of this problem and the recommendations to improve the USAF procedure are twofold. First, guidelines are required to address those cases in which an idealized layered elastic model does not provide realistic moduli values. Second, complementary evaluation approaches could be included in the overall evaluation to fully assess the infrastructure structural condition and improve the pavement evaluation process. In this perspective, the following tasks were identified for the reported research:

- Determine whether currently available backcalculation software used outside the DoD provide more realistic or consistent modulus values for a wide variety of airfield pavement sections including rigid, flexible, and composite pavements using the same deflection basins;
- Investigate complementary approaches in pavement backcalculation and evaluation to help the pavement evaluator determine adequate layer moduli;
- Provide additional procedures for USAF personnel conducting backcalculation analyses to allow both experienced and less experienced users to produce reasonable moduli values for a variety of airfield pavement structures; and if necessary
- Make recommendations to modify the current software.

4 Descriptions of Selected Backcalculation Software and Test Locations

The first step in the analysis process was to compare backcalculation results of selected backcalculation programs using HWD data collected during airfield pavement evaluations. This chapter describes both the backcalculation software and airfield sites used for analysis purposes.

4.1 Selected software for analysis

In addition to the WESDEF program packaged in the PCASE software, two commonly used software programs—BAKFAA and ELMOD6— were selected for evaluation. While these are a small subsection of the available software identified in the literature, these software were selected based on their ability to backcalculate flexible, rigid, and composite pavements. In addition, BAKFAA, ELMOD6, and WESDEF have been successfully applied for backcalculating moduli for airfield pavements, while the other programs have been used primarily for highway or local roadway pavements or for research purposes. The following sections briefly present general information about each program, any unique characteristics of the program, and pertinent observations obtained during program use. A comparison of common characteristics among the backcalculation programs is provided in Table 12.

4.1.1 WESDEF

The basic procedure used by the DoD for the backcalculation of pavement moduli from measured FWD or HWD data was developed in the 1980s. The original five-layer elastic model code, WES5, was written by Frans Van Cauwelaert in 1987 and was modified by Don Alexander in 1989. WESDEF still utilizes this layered elastic model and couples it with a least squares technique to backcalculate moduli that yield a computed deflection basin that best matches the measured deflection basin. WES5 has a maximum limit of five pavement layers in the pavement structure, including a very stiff bottom layer with modulus set to 1,000,000 psi that serves as a rigid boundary (the so-called rigid layer in other backcalculation programs). This layer is set at a depth of 240 in. (20 ft)

Table 12. Comparison of common backcalculation program characteristics.

Program Characteristic	Program		
	WESDEF	BAKFAA	ELMOD6
Inputs			
Pavement Layer Type	√	N/A	√
Thickness	√	√	√
Poisson's Ratio	√	√	√
Subgrade Thickness	√	√	N/A
Max. # of Layers	5	10	5
Ability to Fix Moduli	√	√	√
Depth to Rigid Layer	√	√	√
Backcalculation Settings			
Modulus Limits	√	N/A	N/A
Seed Moduli	√	√	√
Moduli Adjustment	√	√	√
Maximum Iterations	10[a]	5,000	N/A
Deflection Tolerance	7%[a]	N/A	N/A
Modulus Tolerance	7%[a]	N/A	N/A
Ability to Run Outside of Limits	√	N/A	N/A
Iteration Tolerance	N/A	√	N/A
Evaluation Depth	N/A	√	N/A
Outputs			
% Errors	√	Function RMS	% Diff and Function RMS for LET
Representative Basin	√	N/A	N/A (reports mean)
Ability to Change Representative Basin	√	N/A	N/A
Moduli for Each Basin	√	√	√
Measured Deflections	√	√	√
Calculated Deflections	√	√	√

[a] Default value may be adjusted by the user.

unless there is an indication of bedrock at a lesser depth. The other four layers in the pavement system are normally considered to be a surface, base, subbase, and subgrade. The subgrade depth is calculated by the program by subtracting the total pavement thickness above the subgrade from the 240-in. depth to the rigid boundary. While it is possible to backcalculate the moduli for each of the four layers (excluding the rigid bottom layer), practical considerations normally limit the number of backcalculated moduli to three layers or fewer. The software includes default seed moduli, shown in Table 13 that may be adjusted by the user. Additional information, including the error function and screen shots of the software interface for this program, were provided in Chapter 2.

Table 13. Default seed moduli in WESDEF.

Material	Modulus Range		Initial Seed Modulus, psi
	Minimum, psi	Maximum, psi	
AC surface	100,000	1,000,000	350,000
PCC surface	2,500,000	10,000,000	5,000,000
Granular base	5,000	150,000	61,000
High-quality stabilized base	500,000	2,500,000	1,000,000
Base, stabilized	100,000	1,000,000	300,000
Subbase, unstabilized	5,000	150,000	24,000
Subgrade	1,000	50,000	15,000

4.1.2 BAKFAA

BAKFAA is a program created and used by the Federal Aviation Administration (FAA) to backcalculate pavement layer moduli. Like WESDEF, BAKFAA uses a layered elastic program to compute deflections. While the layered elastic code (LEAF) is different from that used in WESDEF (WES5), the program uses a similar iterative method to compute deflections and moduli. This program has the capability to backcalculate up to 10 pavement layers, including a very stiff bottom layer with modulus default value of 60,000 psi (modifiable). This layer may be set to any depth. Seed moduli, Poisson's ratio, layer thickness, and interface parameters (0 for unbonded layer and 1 for bonded layer) must all be entered into the program (Figure 17 shows the program interface). Suggested seed (typical) moduli and moduli ranges for pavement layer types to assist the user are provided in the help menu (Table 14). This program uses a downhill multidimensional simplex minimization method that minimizes the function RMS difference (mils) between the measured and computed deflections using Equation 16.

Figure 17. BAKFAA interface.

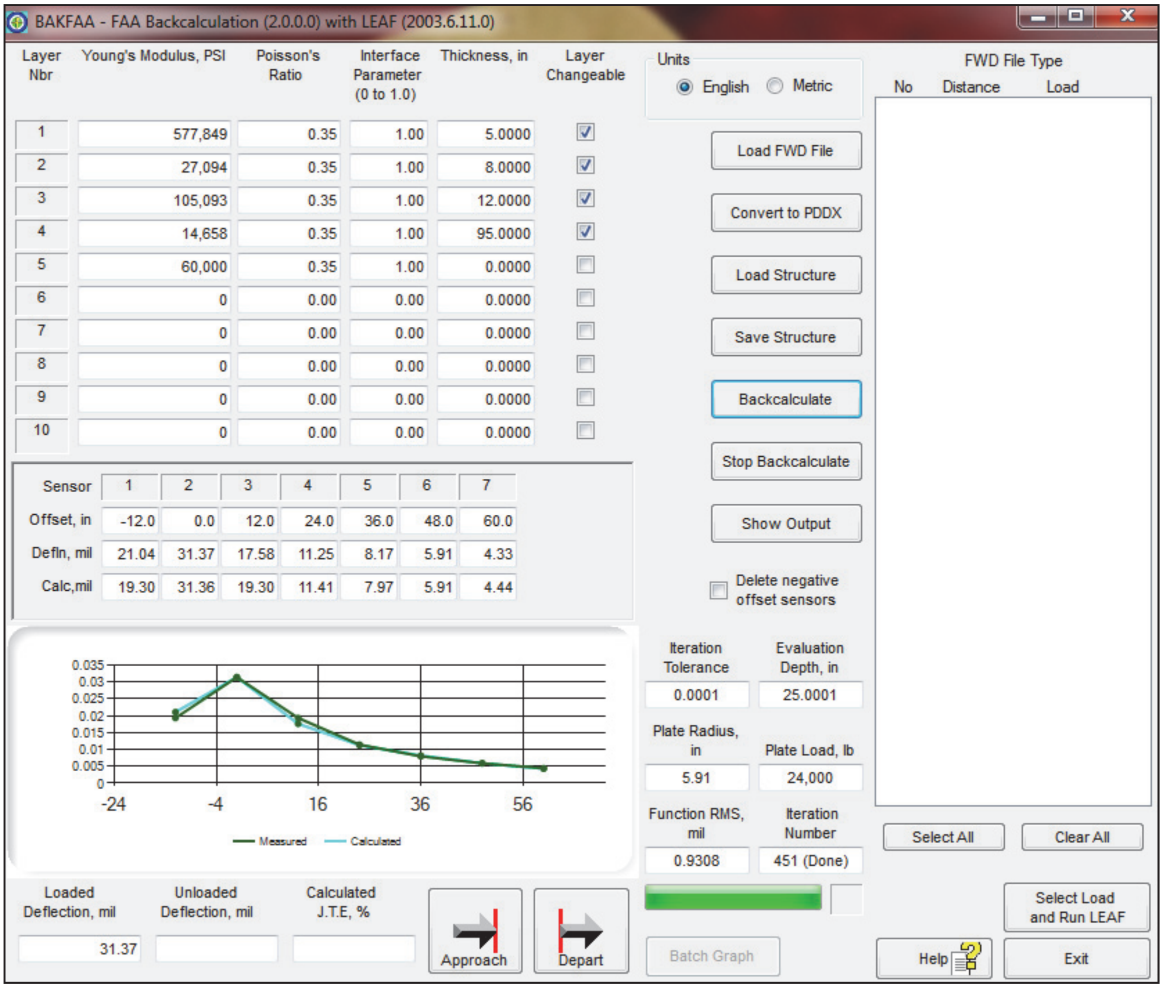


Table 14. Recommended seed moduli for BAKFAA (BAKFAA help menu).

Material	Low Value, psi	High Value, psi	Typical Value, psi
AC surface	70,000	2,000,000	500,000
PCC surface	1,000,000	9,000,000	5,000,000
Lean-concrete base	1,000,000	3,000,000	2,000,000
Asphalt-treated base	100,000	1,500,000	500,000
Cement-treated base	200,000	2,000,000	750,000
Granular base	10,000	50,000	30,000
Granular subbase or soil	5,000	30,000	15,000
Stabilized soil	10,000	200,000	50,000
Cohesive soil	3,000	25,000	7,000

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1,n}(z_{mi} - z_{ci})^2} \tag{16}$$

where:

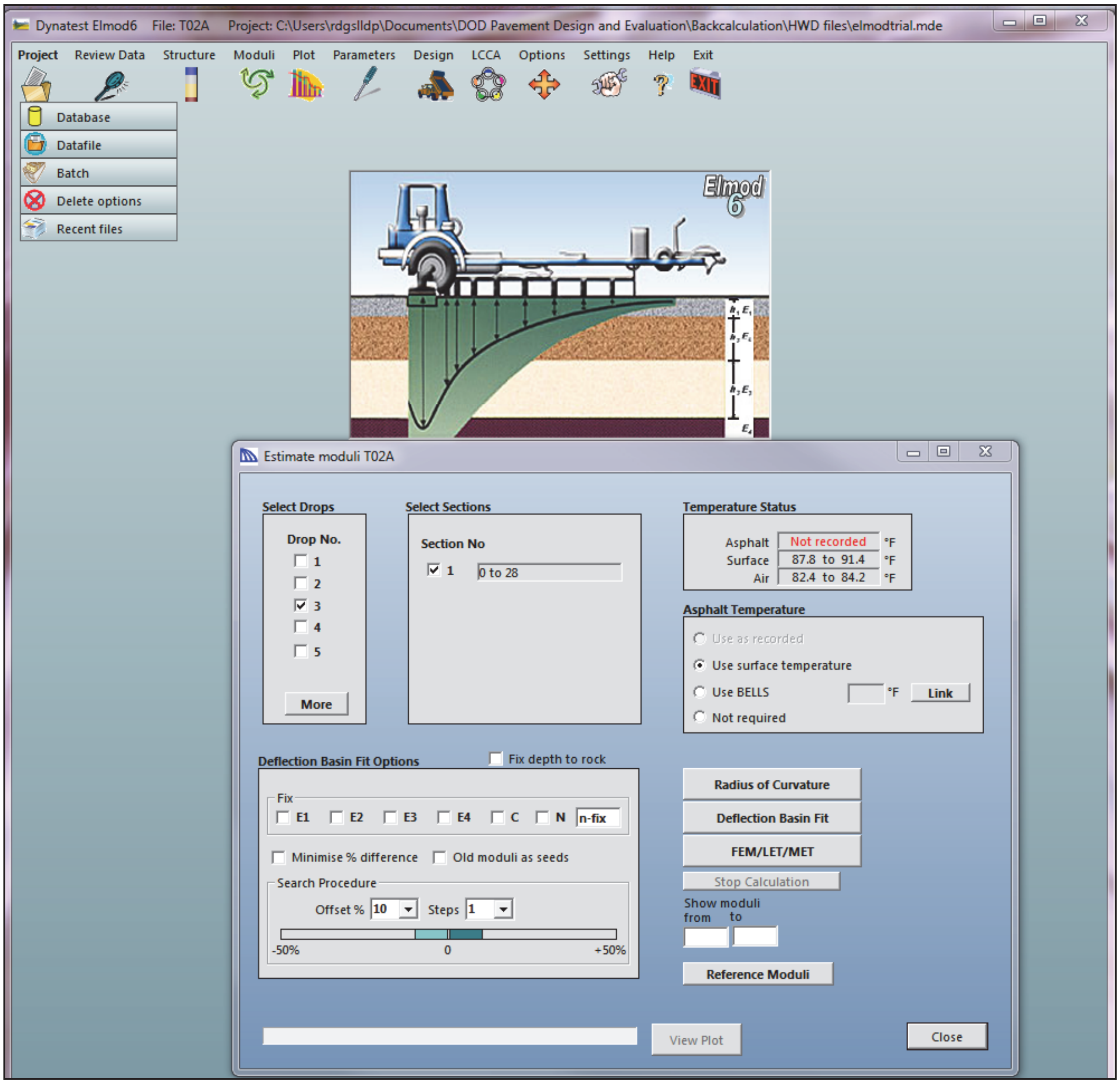
z_{mi} = measured deflection at location of sensor i, mils
z_{ci} = calculated deflection at location of sensor i, mils
n = number of sensors

4.1.3 ELMOD6

Evaluation of Layer Moduli and Overlay Design (ELMOD6) is a program package developed by Dynatest, one of the primary manufacturers of HWD and FWD equipment. This program is used by many FWD/HWD users worldwide. The program can calculate layer moduli for up to five pavement layers. Unlike WESDEF and BAKFAA, this program offers a number of backcalculation approaches. These include the Radius of Curvature approach based on the Odemark-Boussinesq transformed section approach, the Deflection Basin Fit method using a numerical integration technique, or the FEM/LET/MET option that allows the FEM (flexible pavements only), linear elastic theory (LET), or MET approaches to be applied (Figure 18). Of the available approaches, Dynatest recommends the Deflection Basin Fit method for estimating all pavement layer systems (Personal communication with Gabriel Bazi, Dynatest, April 2014).

The Deflection Basin Fit methodology utilizes Odemark's layer transformation approach with Boussinesq's equations to calculate deflections that are computed in an iterative fashion until similar measured and calculated deflections are obtained, and the moduli that would result in those deflections are reported (Dynatest 2014). This program calculates the RMS difference between the measured and the computed deflections using the same equation used for BAKFAA (Equation 16). Seed moduli are not required for this method (they are automatically calculated if using the Deflection Basin Fit methodology); however, seed moduli may be entered, and layer strengths may be fixed to a user input value.

Figure 18. ELMOD6 backcalculation options.



The LET option uses the same general layered elastic model used by WESDEF (referred to as WESLEA by Dynatest) and uses seed moduli input by the user. The depth to the rigid layer may be estimated using the measured deflections in this program. Figure 19 shows the results screen for ELMOD6. Suggested seed moduli are provided in Table 15.

Figure 19. ELMOD6 modulus results screen.

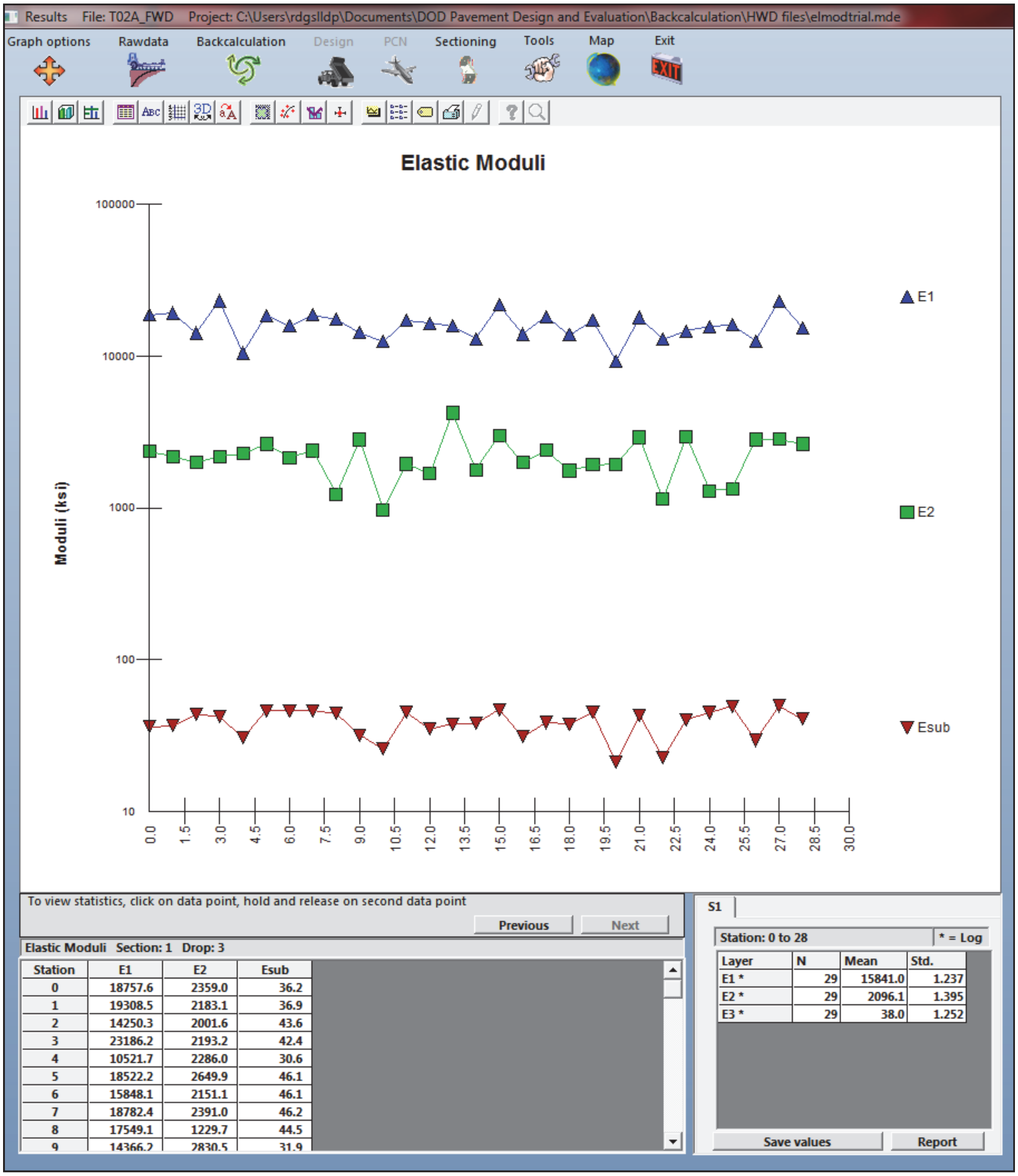


Table 15. ELMOD6 suggested moduli (Dynatest 2014).

Material	Modulus Range	
	Minimum, psi	Maximum, psi
AC surface	400,000	1,000,000
PCC surface	3,000,000	6,000,000
Granular base (generic)	15,000	150,000
Lean concrete base	1,500,000	2,500,000
Unstabilized subbase	15,000	150,000
Subgrade	5,000	50,000

4.2 Selected pavement sections for analysis

A total of 30 pavement sections, consisting of 10 each AC, PCC, and composite pavement sections (AC over PCC), from six airfields were selected for the backcalculation analyses conducted in this study. These airfields and pavement sections were selected in various geographic and climatic regions and have various sublayer conditions and subgrade soil types, as listed in Table 16. The sections were identified from the following airfields:

- Pope Field, Fort Bragg, NC
- Campbell Army Airfield (AAF), Fort Campbell, KY
- Biggs AAF, Fort Bliss, TX
- Wheeler Sack AAF, Fort Drum, NY
- Phillips AAF, Aberdeen Proving Ground, MD
- A511, Camp Humphreys, South Korea

With the exception of Phillips AAF and A511, the airfields selected were major U.S. Army deployment platforms utilizing C-17 aircraft or were former USAF airfields (Pope Field). The selected pavement sections were similar in composition and age as USAF pavements. Additional composite pavement sections (AC over PCC) were selected from Phillips AAF and A511, as 10 composite pavement sections were not available from the other airfields. The availability of actual NDT data, WESDEF backcalculation inputs, and seed moduli used for backcalculating these sections' moduli; the experience of the research team with these pavements; and the historical documentation including as-built drawings, thickness measurements using GPR and Mira, and construction histories for these airfields led to the selection of Army in lieu of USAF airfield pavement sections.

Table 16. Summary of pavement section thicknesses.

Site	Section ID	Airfield	Location	Surface Thick. (in.)	Base Thick. (in.)	Subbase Thick. (in.)	Date of Last HWD Testing
Rigid Pavement Sections							
1	R01A	Pope AAF	NC	12.0	20.0	-	March 2013
2	A27B	Pope AAF	NC	15.5	3.25	0-4.0	March 2013
3	T05A	Pope AAF	NC	15.0	8.0	-	March 2013
4	A22B	Campbell AAF	KY	6.0	-	-	June 2013
5	A14B	Campbell AAF	KY	7.0	-	-	June 2013
6	T02A	Campbell AAF	KY	14.0	17.0	-	June 2013
7	A03B	Biggs AAF	TX	17.5	-	-	October 2011
8	A26B	Biggs AAF	TX	11.0	-	-	October 2011
9	R03A	Biggs AAF	TX	25.0	-	-	October 2011
10	T16A	Biggs AAF	TX	20.0	-	-	October 2011
Flexible Pavement Sections							
1	T23C	Pope AAF	NC	4.5	24.0	-	March 2013
2	A21B	Pope AAF	NC	6.5	6.0	22.0	March 2013
3	R09C2	Pope AAF	NC	8.75	5.0	-	March 2013
4	R10A	Campbell AAF	KY	5.0	10.0	-	June 2013
5	T16C	Campbell AAF	KY	5.0	5.0	15.0	June 2013
6	T07C	Campbell AAF	KY	6.0	9.0	17.0	June 2013
7	T20B	Biggs AAF	TX	4.0	10.0	-	October 2011
8	R11A	Wheeler Sack AAF	NY	8.0	8.0	-	October 2013
9	T02A	Wheeler Sack AAF	NY	6.0	4.0	6.0	October 2013
10	T21B	Wheeler Sack AAF	NY	6.0	4.0	6.0	October 2013
Composite Pavement Sections							
1	A14B	Pope AAF	NC	4.0	6.0	-	March 2013
2	A16B1	Pope AAF	NC	4.5	5.25	14.0	March 2013
3	A16B2	Pope AAF	NC	4.5	5.25	14.0	March 2013
4	R01A	Campbell AAF	KY	11.0	16.0	-	June 2013
5	R11A	Phillips AAF	MD	3.5	6.0	6.0	April 2010
6	R09A	Phillips AAF	MD	4.0	6.0	6.0	April 2010
7	R15A	Phillips AAF	MD	3.0	6.0	6.0	April 2010
8	A05B	A511	Korea	4.0	8.0	-	April 2014
9	A15B	A511	Korea	4.0	8.0	-	April 2014
10	T09B	A511	Korea	4.0	8.0	-	April 2014

All pavement section data— including layer compositions, recent evaluation results, number of deflection points, and the date of the last NDT testing— are presented in Table 17. Layer compositions were obtained from the most recent airfield evaluation report for each airfield, and these thicknesses were based on as-built construction records, coring data, or previous radar testing.

In all cases actual NDT deflection measurements conducted with a Dynatest Model 8082 HWD were used. Routine HWD tests are conducted by the U.S. Army Airfield Pavement Evaluation Team at these airfields (normally every 4 to 8 years), and the collected data are maintained in individual PCASE computer databases for each airfield at the U.S. Army ERDC. Additional details of each airfield and the individual sites are provided in the following sections.

4.2.1 Pope Field, Fort Bragg, NC- Sites 1-3, 11-13, and 21-23

Pope Field, previously Pope Air Force Base, is located adjacent to the northeast boundary of Fort Bragg Army Reservation, NC, approximately 12 miles northwest of Fayetteville, NC. The airfield is located in the sandy hills area of the Atlantic coastal plain. The hills, which are typical of this region, are low and rounded, with shallow valleys between them. The airfield area is relatively flat but is well drained by creeks that bound the field on the east and west. Subgrade soils consist of poorly graded sands, silty sands, and clayey sands. The airfield elevation is approximately 217 ft above sea level.

Nine pavement sections— consisting of three rigid (Sites 1-3), three flexible (Sites 11-13) and three composite (Sites 21-23) sections— were selected at Pope Field. They were evaluated in March 2014 and are summarized as follows:

- The layer compositions for the PCC pavements of Sites 1-3 consisted of three layers: a PCC surface course ranging in thickness from 12.0 to 18.0 in., a base course ranging in thickness from 3.25 to 20.0 in. and composed of various materials (sand, macadam, and well-graded gravel (GW)), and a native silty sand (SM or SW-SM) or sand subgrade (SP-SM).
- The layer compositions for the AC pavements of Sites 11-13 consisted of three or four layers: an AC surface course ranging in thickness from 4.5 to 8.75 in., a base course of sandy gravel (GW-GM) or gravel (GP-GM) ranging in thickness from 5.0 to 24.0 in., a subbase course of clayey sand (SC) ranging from 0.0 to 22.0 in., and a subgrade of varying native materials including sand (SW-SM), clayey sand (SC), or silty sand (SM).

Table 17. Physical property and moduli data for the selected pavement sections.

Site	Sect. ID	Airfield	Installation	Surface Thick., in.	Surface Type	Base Thick, in.	Base Type	Subbase Thick., in.	Subbase Type	Subgrade Type	Layer Modulus, psi				# of Deflect. Test Points	Data Collected Date, mo/year
											Surface	Base	Subbase	Subgrade		
PCC Sections																
1	R01A	Pope Field	Fort Bragg, NC	12.0	PCC	20.0	Sand	-	-	Silty Sand (SM)	4,406,326	46,672	-	26,813	9	3/14
2	A27B	Pope Field	Fort Bragg, NC	15.5	PCC	3.25	Macadam	0.0-4.0	Silty Sand (SW-SM)	Silty Sand (SW-SM)	7,303,390	3,312,134	-	12,870	74	3/14
3	T05A	Pope Field	Fort Bragg, NC	15.0	PCC	8.0	Well Graded Gravel (GW)	-		Sand (SP-SM)	4,309,366	1,769,747	-	20,637	10	3/14
4	A22B	Campbell AAF	Fort Campbell, KY	6.0	PCC	-	-	-	-	Lean Clay (CL)	5,551,901	-	-	12,702	69	6/13
5	A14B	Campbell AAF	Fort Campbell, KY	7.0	PCC	-	-	-	-	Lean Clay (CL)	5,837,475	-	-	21,225	4	6/13
6	T02A	Campbell AAF	Fort Campbell, KY	14.0	PCC	17.0	Crushed Stone (GW)	-	-	Lean Clay (CL)	7,295,389	63,831		14,514	31	6/13
7	A03B	Biggs AAF	Fort Bliss, TX	17.5	PCC	-	-	-	-	Clayey Silty Sand (SM-SC)	8,681,409	-	-	24,148	19	10/11
8	A26B	Biggs AAF	Fort Bliss, TX	11.0	PCC		-		-	Silty Sand (SM)	6,312,345	-	-	29,609	6	10/11
9	R03A	Biggs AAF	Fort Bliss, TX	25.0	PCC	-	-	-	-	Silty Sand (SM) and Clayey Sand (SC)	9,120,589	-	-	20,473	6	10/11

Site	Sect. ID	Airfield	Installation	Surface Thick., in.	Surface Type	Base Thick, in.	Base Type	Subbase Thick., in.	Subbase Type	Subgrade Type	Layer Modulus, psi				# of Deflect. Test Points	Data Collected Date, mo/year
											Surface	Base	Subbase	Subgrade		
10	T16A	Biggs AAF	Fort Bliss, TX	20.0	PCC	-	-	-	-	Clayey Silty Sand (SM-SC)	9,241,213	-	-	18,593	9	10/11
AC Sections																
11	T23C	Pope Field	Fort Bragg, NC	4.5	AC	24.0	Sandy Gravel (GW-GM)	-	-	Sand (SW-SM)	1,580,224	41,627	-	16,553	8	3/14
12	A21B	Pope Field	Fort Bragg, NC	6.5	AC	6.0	Gravel (GP-GM)	22.0	Clayey Sand (SC)	Clayey Sand (SC)	650,714	41,036	25,605	16,891	5	3/15
13	R09C2	Pope Field	Fort Bragg, NC	8.75	AC	5.0	Gravel (GP-GM)	-	-	Silty Sand (SM)	1,045,359	226,795	-	22,079	12	3/16
14	R10A	Campbell AAF	Fort Campbell, KY	5.0	AC	10.0	Crushed Stone (GW)	-	-	Lean Clay (CL)	274,665	14,405	-	26,938	24	6/13
15	T16C	Campbell AAF	Fort Campbell, KY	5.0	AC	5.0	Crushed Stone (GW)	15.0	Dense-Graded Aggregate	Lean Clay (CL)	311,323	53,052	16,333	23,270	6	6/13
16	T07C	Campbell AAF	Fort Campbell, KY	6.0	AC	9.0	Water-Bound Macadam	17.0	Crushed Stone (GW)	Lean Clay (CL)	314,437	73,448	32,870	28,847	8	6/13
17	T20B	Biggs AAF	Fort Bliss, TX	4.0	AC	10.0	Clayey Sandy Gravel	-	-	Silty Sand (SM)	950,941	39,977	-	27,485	3	10/11
18	R11A	Wheeler Sack AAF	Fort Drum, NY	8.0	AC	8.0	Aggregate Base	-	-	Sand (SP)	999,991	166,307	-	16,670	11	10/13
19	T02A	Wheeler Sack AAF	Fort Drum, NY	6.0	AC	4.0	Granular Base	6.0	Granular Subbase	Sand (SP)	597,265	129,726	Combined with Base	21,310	14	10/13
20	T21B	Wheeler Sack AAF	Fort Drum, NY	6.0	AC	4.0	Granular Base	6.0	Granular Subbase	Sand (SP)	488,230	99,839	Combined with Base	18,395	22	10/13

Site	Sect. ID	Airfield	Installation	Surface Thick., in.	Surface Type	Base Thick, in.	Base Type	Subbase Thick., in.	Subbase Type	Subgrade Type	Layer Modulus, psi				# of Deflect. Test Points	Data Collected Date, mo/year
											Surface	Base	Subbase	Subgrade		
Composite Sections																
21	A14B	Pope Field	Fort Bragg, NC	4.0	AC	6.0	PCC			Silty Sand (SM)	526,588	4,877,044		16,600	12	3/14
22	A16B1	Pope Field	Fort Bragg, NC	4.5	AC	5.25	PCC	14.0	Stabilized Silty Sand	Sandy Clay (SC)	535,532	3,707,517	Combined with Subgrade	22,863	7	3/15
23	A16B2	Pope Field	Fort Bragg, NC	4.5	AC	5.25	PCC	14.0	Stabilized Silty Sand	Sandy Clay (SC)	1,287,990	211,083	Combined with Subgrade	15,948	3	3/16
24	R01A	Campbell AAF	Fort Campbell, KY	11.0	AC	16.0	PCC			Lean Clay (CL)	607,490	4,200,487		27,740	11	6/13
25	R11A	Phillips AAF	Aberdeen Proving Ground, MD	3.5	AC	6.0	PCC	6.0	Silty Sandy Gravel (GP-GM)	Sandy Clay (SL)	55,465	225,000	Combined with Subgrade	18,065	2	4/10
26	R09A	Phillips AAF	Aberdeen Proving Ground, MD	4.0	AC	6.0	PCC	6.0	Silty Sandy Gravel (GM)	Sandy Clay (SL)	556,267	225,000	Combined with Subgrade	9,227	3	4/10
27	R15A	Phillips AAF	Aberdeen Proving Ground, MD	3.0	AC	6.0	PCC	6.0	Silty Gravelly Sand (SM)	Sandy Clay (SL)	225,112	101,095	Combined with Subgrade	17,488	2	4/10
28	A05B	A511	Pyongtaek, Korea	4.0	AC	8.0	PCC			Sandy Clay (CL)	445,950	10,581,681		19,303	6	4/14
29	A15B	A511	Pyongtaek, Korea	4.0	AC	8.0	PCC			Sandy Clay (CL)	424,161	3,442,336		11,696	6	4/14
30	T09B	A511	Pyongtaek, Korea	4.0	AC	8.0	PCC			Sandy Clay (CL)	884,141	3,000,784		13,500	3	4/14

- The layer compositions for the composite pavements of Sites 21-23 consisted of three or four layers: an AC surface course ranging in thickness from 4.0 to 4.5 in., a PCC base layer ranging in thickness from 5.25 to 6.0 in., a subbase course of stabilized silty sand (no USCS classification) ranging in thickness from 0.0 to 14.0 in., and a subgrade of varying native materials including SM or SC.

4.2.2 Campbell AAF, Fort Campbell, KY- Sites 4-6, 14-16, and 24

Campbell AAF is located on the reservation of Fort Campbell, KY, approximately 10 miles north of Clarksville, TN, and 15 miles south of Hopkinsville, KY, along U.S. Highway 41. The subgrade soils in the immediate area of the airfield fall generally into the lean clay (CL) classification. The ground surface is generally rolling with grades up to 15 percent; the average is approximately 3 percent. The airfield elevation is approximately 571 ft above sea level.

Seven pavement sections— consisting of three rigid (Sites 4-6), three flexible (Sites 14-16), and one composite (Site 24)— were selected at Campbell AAF. They were evaluated in June 2013 and are summarized as follows:

- The layer compositions for the PCC pavements of Sites 4-6 consisted of two or three layers: a PCC surface course ranging in thickness from 6.0 to 14.0 in. and a base course ranging in thickness from 0.0 to 17.0 in. composed of crushed stone (GW), and a native CL subgrade.
- The layer compositions for Sites 14-16 consisted of three or four layers: an AC surface course ranging in thickness from 5.0 to 6.0 in., a base course consisting of 5.0 to 10.0 in. of crushed stone (GW) or 9.0 in. of water-bound macadam, a subbase course consisting of 0.0 to 17.0 in. of dense-graded aggregate or crushed stone (GW), and a native CL subgrade.
- The layer composition of Site 24 consisted three layers: an AC surface course of 11.0 in., a PCC base layer of 16.0 in., and a native CL subgrade.

4.2.3 Biggs AAF, Fort Bliss, TX- Sites 7-10 and 17

BAAF is located at Fort Bliss, Texas, in El Paso County, El Paso, TX. The airfield is located physiologically in the Huaco Basin, a feature of the Mexican Highland section of the Basin and Range Province of the Intermontane Plains. The native subgrade soils in the area are generally reddish, slightly clayey, silty sands with caliche at lower depths typically falling into the soil classifications of SM or SM-SC. The elevation of the airfield is 3,946 ft above mean sea level.

Five pavement sections were selected at Biggs AAF, including four rigid (Sites 7-10) and one flexible (Site 17). They were evaluated in November 2011 and are summarized as follows:

- The layer compositions for the PCC pavements of Sites 7-10 consisted of two layers: a PCC surface course ranging in thickness from 11.0 to 25.0 in. and a native clayey silty sand (SM-SC) or silty sand (SM) subgrade.
- The layer composition for Site 17 consisted of three layers: an AC surface course with thickness of 4.0 in., a base course consisting of 10.0 in. of clayey sandy gravel, and a native SM subgrade.

4.2.4 Wheeler Sack AAF, Fort Drum, NY- Sites 18-20

Wheeler Sack AAF is located in the southeast portion of the Fort Drum Military Reservation and approximately 12 miles northwest of Watertown, NY, in Jefferson County. Geologically, the sand plains of this area are features of a former shoreline bordering a lake that existed during the glacial history of the region. The sands represent former beaches and bars that have since been reworked and modified by wind action, resulting in a subgrade soil classification of poorly graded sand (SP). The elevation of the airfield is 690 ft above mean sea level.

Three flexible pavement sections (Sites 18-20) selected at Wheeler Sack AAF and evaluated in October 2013 are summarized as follows:

- The layer compositions for Sites 18-20 consisted of three or four layers: a surface course ranging in thickness from 6.0 to 8.0 in. of AC, a base course consisting of 4.0 to 9.0 in. of either granular base material or aggregate base material (no USCS classification), a subbase course consisting of 4.0 to 6.0 in. of granular subbase (no USCS classification), and a native SP subgrade.

4.2.5 Phillips AAF, Aberdeen Proving Ground, MD- Sites 25-27

Phillips AAF is located at Aberdeen Proving Ground, MD, approximately 2 miles south of the city of Aberdeen in Harford County, MD. It is located on the Chesapeake Bay about 80 miles from the Atlantic Ocean. The airfield is located on the North Atlantic Coastal Plain. The area is generally flat and has low topography with alluvial soils, consisting of lean or sandy clay (CL) and sandy silt (ML). The elevation of the airfield is 57 ft above mean sea level.

Three composite pavement sections (Sites 25-27) selected at Phillips were evaluated in April 2010 as summarized as follows:

- The layer compositions for Sites 25-27 consisted of four layers: an AC surface course ranging in thickness from 3.0 to 4.0 in., a PCC base of 6.0 in., a subbase course of silty sandy gravel (GP-GM or GM) of 6.0 in., and a native CL subgrade.

4.2.6 A511, Camp Humphreys, South Korea- Sites 28-30

A511 is located at Camp Humphreys, South Korea. Camp Humphreys is adjacent to the seaport city of Pyongtaek, approximately 35 miles south of Seoul. The garrison is situated approximately 12 miles east of the Asan Bay, and the airfield is situated 3 miles southeast of the Ansong River. The area is generally flat with some rolling hills in the general vicinity with elevations less than 150 ft with soils generally consisting of sandy clay (CL). The elevation of the airfield is 52 ft above mean sea level.

Three composite pavement sections (Sites 28-30) selected at A511 were evaluated in April 2014 as summarized as follows:

- The layer compositions for Sites 28-30 consisted of three layers: an AC surface course with thickness of 4.0 in., a PCC base of 8.0 in., and a native CL subgrade.

5 Analysis

5.1 Backcalculation with selected software

5.1.1 WESDEF

HWD deflection data for each pavement section were imported into the PCASE software. Following this step, two different analyses were conducted with WESDEF in PCASE. The first was the inexperienced user method in which the general backcalculation guidance provided in Chapter 2 was followed by the user with no adjustments made to the seed moduli (using the default values shown previously in Table 13). The backcalculation was conducted both with and without forcing the moduli to stay within the seed moduli limits following the current USAF procedure. Two- to four-layer systems were backcalculated based upon the existence of sublayers. These values were then compared to the expert user method in which the seed moduli and or the layer moduli were fixed based on the engineering judgment of the user. These expert moduli were based upon the published airfield pavement evaluation results for the airfields selected for analyses. While it is not the current USAF practice to modify the seed moduli, often the USAF will fix the pavement layer moduli based on engineering judgment or DCP test results. In all cases, multiple deflection basins were used for each pavement feature, and the WESDEF moduli associated with the representative basin were reported.

5.1.2 BAKFAA

To conduct backcalculation in BAKFAA, no HWD files were imported. While BAKFAA allows the user to import multiple deflection basins directly from HWD files, the software does not select a representative basin; it simply returns the backcalculated moduli for each basin for the user to either average or select the representative moduli values for the pavement section. For direct comparison between the moduli computed by this program and WESDEF, the representative basin deflections and load level identified in PCASE were used.

To use the software, the seed moduli, Poisson’s ratio, layer thickness, plate load, and representative deflection basin were manually entered into the program. Two different analyses similar to those discussed for WESDEF were then conducted in BAKFAA. The first used the expert seed moduli to conduct the backcalculation process (expert user method); the seed moduli used to obtain the WESDEF expert moduli values were used in order to obtain a direct comparison of the BAKFAA moduli values to the WESDEF expert moduli values. The second analysis was then performed using the typical seed values that are found in the help menu of the BAKFAA program (inexperienced user method). The typical values were used to determine whether the results from these values would vary significantly from those obtained using the expert seed moduli.

It should be noted that unlike WESDEF, no maximum or minimum modulus values are input into the program, only the seed moduli values for each pavement layer. Also, as mentioned before, for comparison purposes to the expert moduli, the deflection basin that was manually typed into BAKFAA was the representative basin chosen during the WESDEF analyses. Other inputs that differed from WESDEF included entering a plate radius (default of 5.9 in.) and the evaluation depth (preset to 25 in.). The evaluation depth was changed to 240 in. to match the structure evaluated in WESDEF. Another important input was the modulus of the rigid layer. Unlike WESDEF, BAKFAA populates an extra layer to be the rigid layer, and all values in that layer are set to zero with the exception of the Young's modulus, which is set by the user. For comparison with WESDEF, this value was set to 1,000,000 psi. When the backcalculate command was executed, the program created a new calculated deflection basin and provided the function RMS between the measured and computed deflection basins. The new deflection basin and the function RMS values were recorded.

5.1.3 ELMOD6

Like WESDEF, the HWD deflection data for each pavement section were imported into the software. Three different analyses were then conducted with ELMOD6. The first used the deflection basin fit option methodology, and the second and third used the LET option following the inexperienced user method using default seed moduli and the expert user method using expert seed moduli described in the previous sections.

Like BAKFAA, for the deflection basin fit option, no representative basin was identified; all moduli for each HWD test location were reported by the program. Unlike BAKFAA, the mean moduli value for each pavement layer was reported. For comparisons to WESDEF, both the mean moduli for the pavement layer and the moduli returned for the representative station identified during the WESDEF analyses were recorded. Using this option, no seed moduli are specified requiring no engineering judgment (inexperienced user method).

For the LET option (experienced user method), seed moduli values were entered, along with Poisson's ratio and the maximum and minimum modulus values. The seed values that were used were the same seed values used in WESDEF for the expert results.

5.1.4 Results

5.1.4.1 WESDEF

The modulus results for each pavement section were compared to the previously published results completed by experienced backcalculation users. Because the true moduli were unknown, the published results or expert results were considered to be adequate results for initial comparison purposes. The expert modulus results reported in Table 18 are those that WESDEF identified as the representative basin or the station where the moduli are considered representative of the pavement structure (least error between calculated and measured layer moduli). Both the results from the experienced user method and the inexperienced user method are presented in this table.

5.1.4.2 BAKFAA

The modulus results for each pavement section using BAKFAA were compared to the WESDEF expert results in Table 19. As mentioned previously, two methods of analysis were used: the experienced user method, using the same seed moduli as used for the WESDEF expert results, and the inexperienced user method, using the typical seed values recommended by BAKFAA. The experienced user results are reported under the expert seed column, and the inexperienced user results are reported under the typical seed column.

5.1.4.3 ELMOD6

The modulus results for each pavement section using ELMOD6 were compared to the WESDEF expert results in Table 20. As mentioned previously, both the inexperienced user method using the deflection basin fit method and the expert method using the same seed moduli using the LET method were used.

Table 18. Comparison of WESDEF results.

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			Experienced User Method		Inexperienced User Method Results[c]					
			Expert Results[a]	% Error[b]	Limits on	% Error[b]	% Diff.[d]	Limits off	% Error[b]	% Diff.[d]
Pope Field										
	PCC	PCC	4,406,326		4,058,277		7.90	4,406,326		0.00
	Base	Sand	46,672	0.90	39,257	0.60	15.89	46,672	0.90	0.00
R01A	Natural Subgrade	SM	26,813		22,082		17.64	26,813		0.00
	PCC	PCC	7,303,390		7,892,199		8.06	7,303,390		0.00
	HQ Stab Base	Macadam	3,312,134	2.40	4,011,167	0.80	21.11	3,312,134	2.40	0.00
A27B	Comp Subgrade	SW-SM	12,870		15,336		19.16	12,870		0.00
	PCC	PCC	4,309,366		6,282,110		45.78	4,309,366		0.00
	Base	GW	1,769,747	0.50	150,000	0.50	91.52	1,769,747	0.50	0.00
T05A	Comp Subgrade	SP-SM	20,637		23,568		14.20	20,637		0.00
	Asphalt	AC	1,580,224		1,581,671		0.09	1,580,224		0.00
	Base	GW-GM	41,627	1.70	41,601	1.70	0.06	41,627	1.70	0.00
T23C	Natural Subgrade	SW-SM	16,553		16,558		0.03	16,553		0.00
	Asphalt	AC	650,714		650,714		0.00	638,519		1.87
	Base	GP-GM	41,036	0.70	41,036	0.70	0.00	41,744	1.00	1.73
	Subbase	SC	25,605		25,605		0.00	26,436		3.25
A21B	Natural Subgrade	SC	16,891		16,891		0.00	16,856		0.21
	Asphalt	AC	1,045,359		1,000,000		4.34	1,000,795		4.26
	Base	GP-GM	226,795	2.20	150,000	5.60	33.86	306,348	1.70	35.08
R09C2	Comp Subgrade	SM	22,079		26,490		19.98	25,112		13.74
	Asphalt	AC	526,588		603,625		14.63	620,661		17.86
	HQ Stab Base	PCC	4,877,044	2.60	4,355,680	2.60	10.69	4,113,237	2.70	15.66
A14B	Comp Subgrade	SM	16,600		16,635		0.21	16,657		0.34
	Asphalt	AC	535,532		573,855		7.16	479,288		10.50
	HQ Stab Base	PCC	3,707,517	2.00	3,464,625	1.90	6.55	3,725,312	2.50	0.48
A16B1	Comp Subgrade	SC	22,863		22,907		0.19	22,865		0.01

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			Experienced User Method		Inexperienced User Method Results[c]					
			Expert Results[a]	% Error[b]	Limits on	% Error[b]	% Diff.[d]	Limits off	% Error[b]	% Diff.[d]
	Asphalt	AC	1,287,990	3.70	369,115	11.50	71.34	1,287,980	3.70	0.00
	HQ Stab Base	PCC	211,083		500,000		136.87	211,089		0.00
A16B2	Comp Subgrade	SC	15,948		18,895		18.48	15,948		0.00
Campbell AAF										
	PCC	PCC	5,551,901	1.40	5,539,264	1.40	0.23	5,544,004	1.40	0.14
A22B	Natural Subgrade	CL	12,702		12,709		0.06	12,707		0.04
	PCC	PCC	5,837,475	2.10	5,832,900	2.10	0.08	5,836,234	2.10	0.02
A14B	Natural Subgrade	CL	21,225		21,232		0.03	21,227		0.01
	PCC	PCC	7,295,389	0.80	7,295,389	0.80	0.00	7,295,389	0.80	0.00
	Base	GW	63,831		63,831		0.00	63,831		0.00
T02A	Comp Subgrade	CL	14,514		14,514		0.00	14,514		0.00
	Asphalt	AC	274,665	11.10	300,650	3.60	9.46	300,303	3.60	9.33
	Base	GW	14,405		11,588		19.56	11,585		19.58
R10A	Natural Subgrade	CL	26,938		26,648		1.08	26,649		1.07
	Asphalt	AC	311,323	0.70	311,323	0.70	0.00	311,348	0.90	0.01
	Base	GW	53,052		53,052		0.00	52,919		0.25
	Subbase	Dense Graded Aggregate	16,333		16,333		0.00	16,412		0.48
T16C	Natural Subgrade	CL	23,270		23,270		0.00	23,353		0.36
	Asphalt	AC	314,437	1.50	314,437	1.50	0.00	315,470	1.50	0.33
	Base	Water-Bound Macadam	73,448		73,448		0.00	73,081		0.50
	Subbase	GW	32,870		32,870		0.00	32,934		0.19
T07C	Comp Subgrade	CL	28,847		28,847		0.00	28,832		0.05
	Asphalt	AC	607,490	1.10	603,410	1.10	0.67	607,506	1.10	0.00
	HQ Stab Base	PCC	4,200,487		4,218,993		0.44	4,199,773		0.02
R01A	Natural Subgrade	CL	27,740		27,750		0.04	27,739		0.00

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			Experienced User Method		Inexperienced User Method Results[c]					
			Expert Results[a]	% Error[b]	Limits on	% Error[b]	% Diff.[d]	Limits off	% Error[b]	% Diff.[d]
Biggs AAF										
	PCC	PCC	8,681,409	0.80	6,161,896	4.50	29.02	8,743,264	0.80	0.71
A03B	Comp Subgrade	SM-SC	24,148		22,470		6.95	23,897		1.04
	PCC	PCC	6,312,345	1.50	6,315,491	1.50	0.05	6,318,388	1.50	0.10
A26B	Comp Subgrade	SM	29,609		29,569		0.14	29,634		0.08
	PCC	PCC	9,120,589	0.80	6,683,451	1.10	26.72	8,036,184	0.70	11.89
R03A	Comp Subgrade	SM-SC	20,473		35,141		71.65	21,263		3.86
	PCC	PCC	9,214,213	0.50	8,397,435	0.50	8.86	9,255,958	0.50	0.45
T16A	Comp Subgrade	SM-SC	18,593		21,228		14.17	18,587		0.03
	Asphalt	AC	950,941		252,904		73.40	947,263		0.39
	Base	Clayey Sandy Gravel	39,977	11.80	31,353	5.90	21.57	40,124	11.80	0.37
T20B	Comp Subgrade	SM	27,485		22,145		19.43	27,483		0.01
Wheeler Sack AAF										
	Asphalt	AC	999,991		1,000,000		0.00	1,344,817		34.48
	Base	Aggregate Base	166,307	2.50	167,468	1.40	0.70	146,070	3.30	12.17
R11A	Natural Subgrade	SP	16,670		16,226		2.66	16,585		0.51
	Asphalt	AC	597,265		677,133		13.37	607,952		1.79
	Base	Granular Base	129,726	3.40	112,553	2.70	13.24	128,211	3.40	1.17
T02A	Natural Subgrade	SP	21,310		19,435		8.80	21,312		0.01
	Asphalt	AC	488,230		488,075		0.03	558,773		14.45
	Base	Granular Base	99,839	3.00	99,845	3.00	0.01	90,745	2.60	9.11
T21B	Natural Subgrade	SP	18,395		18,395		0.00	19,795		7.61
Phillips AAF										
	Asphalt	AC	55,465		28,579		48.47	1,344,817		2324.62
	Stab Base	PCC	225,000	13.50	712,999	14.60	216.89	146,070	3.30	35.08
R11A	Comp Subgrade	SL	18,065		16,755		7.25	16,585		8.19
R09A	Asphalt	AC	556,267	4.70	100,000	2.90	82.02	74,981	1.70	86.52

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			Experienced User Method		Inexperienced User Method Results[c]					
			Expert Results[a]	% Error[b]	Limits on	% Error[b]	% Diff.[d]	Limits off	% Error[b]	% Diff.[d]
	Stab Base	PCC	225,000		1,000,000		344.44	1,539,875		584.39
	Comp Subgrade	SL	9,227		8,927		3.25	9,292		0.70
	Asphalt	AC	225,112		811,063		260.29	2,672,129		1087.02
	Stab Base	PCC	101,095	7.50	49,312	7.70	51.22	14,359	5.00	85.80
R15A	Comp Subgrade	SL	17,488		16,736		4.30	18,143		3.75
A511										
	Asphalt	AC	445,950		445,198		0.17	746,746		67.45
	HQ Stab Base	PCC	10,581,681	1.30	10,587,054	1.30	0.05	10,000,000	27.70	5.50
A05B	Natural Subgrade	CL	19,303		19,302		0.01	13,817		28.42
	Asphalt	AC	424,161		424,161		0.00	338,678		20.15
	HQ Stab Base	PCC	3,442,336	0.60	3,442,336	0.60	0.00	4,276,992	1.40	24.25
A15B	Natural Subgrade	CL	11,696		11,696		0.00	10,913		6.69
	Asphalt	AC	884,141		884,141		0.00	2,414,290		173.07
	HQ Stab Base	PCC	3,000,784	0.60	3,000,784	0.60	0.00	1,319,288	0.50	56.04
T09B	Natural Subgrade	CL	13,500		13,500		0.00	13,373		0.94

[a] Expert results reported during most recent pavement evaluation using expert seed moduli.

[b] % Error is the error reported by WESDEF.

[c] Inexperienced user results using default seed moduli.

[d] Between expert and inexperienced user results.

Table 19. Comparison of BAKFAA and WESDEF results.

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
					BAKFAA Results					
					Experienced User Method			Inexperienced User Method		
			WESDEF Results[a]	% Error[b]	Expert Seed[c]	RMS[d],mils	% Diff.[e]	Typical Seed[f]	RMS[d],mils	% Diff.[e]
Pope Field										
	PCC	PCC	4,406,326		4,503,865		2.21	4,496,294		2.04
	Base	Sand	46,672	0.90	33,455	0.08	28.32	33,810	0.08	27.56
R01A	Natural Subgrade	SM	26,813		27,089		1.03	27,045		0.87
	PCC	PCC	7,303,390		7,549,188		3.37	7,449,287		2.00
	HQ Stab Base	Macadam	3,312,134	2.40	945,777	0.07	71.45	1,080,609	0.07	67.37
A27B	Comp Subgrade	SW-SM	12,870		12,707		1.27	12,693		1.38
	PCC	PCC	4,309,366		6,084,615		41.20	6,217,408		44.28
	Base	GW	1,769,747	0.50	66,749	0.09	96.23	35,207	0.10	98.01
T05A	Comp Subgrade	SP-SM	20,637		21,810		5.68	22,182		7.49
	Asphalt	AC	1,580,224		1,425,258		9.81	1,425,367		9.80
	Base	GW-GM	41,627	1.70	43,588	0.10	4.71	43,582	0.10	4.70
T23C	Natural Subgrade	SW-SM	16,553		16,506		0.28	16,508		0.27
	Asphalt	AC	650,714		635,790		2.29	635,908		2.28
	Base	GP-GM	41,036	0.70	38,566	0.06	6.02	38,546	0.06	6.07
	Subbase	SC	25,605		26,127		2.04	26,135		2.07
A21B	Natural Subgrade	SC	16,891		16,879		0.07	16,877		0.08
	Asphalt	AC	1,045,359		1,112,611		6.43	1,156,646		10.65
	Base	GP-GM	226,795	2.20	127,804	0.17	43.65	110,441	0.17	51.30
R09C2	Comp Subgrade	SM	22,079		22,196		0.53	22,262		0.83
	Asphalt	AC	526,588		1,124,136		113.48	1,134,431		115.43
	HQ Stab Base	PCC	4,877,044	2.60	2,576,122	0.48	47.18	2,553,072	0.48	47.65
A14B	Comp Subgrade	SM	16,600		16,389		1.27	16,381		1.32

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			WESDEF Results[a]	% Error[b]	BAKFAA Results					
					Experienced User Method			Inexperienced User Method		
					Expert Seed[c]	RMS[d],mils	% Diff.[e]	Typical Seed[f]	RMS[d],mils	% Diff.[e]
	Asphalt	AC	535,532		539,656		0.77	916,336		71.11
	HQ Stab Base	PCC	3,707,517	2.00	3,925,293	0.25	5.87	1,975,645	0.31	46.71
A16B1	Comp Subgrade	SC	22,863		22,641		0.97	22,639		0.98
	Asphalt	AC	1,287,990		875,958		31.99	1,084,827		15.77
	HQ Stab Base	PCC	211,083	3.70	339,787	0.45	60.97	290,470	0.46	37.61
A16B2	Comp Subgrade	SC	15,948		16,126		1.12	16,113		1.03
Campbell AAF										
	PCC	PCC	5,551,901	1.40	5,501,352	0.29	0.91	5,504,092	0.29	0.86
A22B	Natural Subgrade	CL	12,702		12,512		1.50	12,509		1.52
	PCC	PCC	5,837,475	2.10	5,674,756	0.24	2.79	5,673,704	0.24	2.81
A14B	Natural Subgrade	CL	21,225		20,806		1.97	20,808		1.96
	PCC	PCC	7,295,389		6,928,318		5.03	6,787,162		6.97
	Base	GW	63,831	0.80	40,263	0.06	36.92	51,577	0.06	19.20
T02A	Comp Subgrade	CL	14,514		14,892		2.60	14,687		1.19
	Asphalt	AC	274,665		333,214		21.32	332,342		21.00
	Base	GW	14,405	11.10	13,503	0.36	6.26	13,558	0.36	5.88
R10A	Natural Subgrade	CL	26,938		27,729		2.94	27,674		2.73
	Asphalt	AC	311,323		302,810		2.73	523,625		68.19
	Base	GW	53,052	0.70	55,922	0.04	5.41	52,418	0.41	1.20
	Subbase	Dense Graded Aggregate	16,333		15,991		2.09	7,919		51.52
T16C	Natural Subgrade	CL	23,270		23,443		0.74	21,558		7.36
	Asphalt	AC	314,437		304,844		3.05	307,518		2.20
	Base	Water-Bound Macadam	73,448		79,103		7.70	78,014		6.22
	Subbase	GW	32,870	1.50	30,968	0.12	5.79	31,255	0.12	4.91
T07C	Comp Subgrade	CL	28,847		29,314		1.62	29,260		1.43

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
					BAKFAA Results					
			WESDEF Results[a]	% Error[b]	Experienced User Method			Inexperienced User Method		
					Expert Seed[c]	RMS[d],mils	% Diff.[e]	Typical Seed[f]	RMS[d],mils	% Diff.[e]
	Asphalt	AC	607,490		616,587		1.50	615,772		1.36
	HQ Stab Base	PCC	4,200,487	1.10	4,238,198	0.07	0.90	4,256,020	0.07	1.32
R01A	Natural Subgrade	CL	27,740		27,518		0.80	27,502		0.86
Biggs AAF										
	PCC	PCC	8,681,409	0.80	8,429,208	0.07	2.91	8,426,667	0.07	2.93
A03B	Comp Subgrade	SM-SC	24,148		23,898		1.04	23,903		1.01
	PCC	PCC	6,312,345	1.50	5,884,091	0.21	6.78	5,882,253	0.21	6.81
A26B	Comp Subgrade	SM	29,609		29,627		0.06	29,627		0.06
	PCC	PCC	9,120,589	0.80	9,368,471	0.04	2.72	9,353,244	0.04	2.55
R03A	Comp Subgrade	SM-SC	20,473		19,659		3.98	19,687		3.84
	PCC	PCC	9,214,213	0.50	8,914,572	0.05	3.25	8,918,771	0.05	3.21
T16A	Comp Subgrade	SM-SC	18,593		18,625		0.17	18,621		0.15
	Asphalt	AC	950,941		962,516		1.22	959,884		0.94
	Base	Clayey Sandy Gravel	39,977	11.80	38,862	0.66	2.79	38,917	0.66	2.65
T20B	Comp Subgrade	SM	27,485		28,233		2.72	28,222		2.68
Wheeler Sack AAF										
	Asphalt	AC	999,991		1,067,223		6.72	1,069,594		6.96
	Base	Aggregate Base	166,307	2.50	145,285	0.46	12.64	145,071	0.46	12.77
R11A	Natural Subgrade	SP	16,670		16,864		1.16	16,858		1.13
	Asphalt	AC	597,265		788,199		31.97	783,608		31.20
	Base	Granular Base	129,726	3.40	106,109	0.48	18.21	106,878	0.48	17.61
T02A	Natural Subgrade	SP	21,310		21,588		1.30	21,575		1.24
	Asphalt	AC	488,230		645,372		32.19	645,092		32.13
	Base	Granular Base	99,839	3.00	81,131	0.39	18.74	81,085	0.39	18.78
T21B	Natural Subgrade	SP	18,395		18,515		0.65	18,516		0.66

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			WESDEF Results[a]	% Error[b]	BAKFAA Results					
					Experienced User Method			Inexperienced User Method		
					Expert Seed[c]	RMS[d],mils	% Diff.[e]	Typical Seed[f]	RMS[d],mils	% Diff.[e]
Phillips AAF										
R11A	Asphalt	AC	55,465	13.50	108,368	1.22	95.38	28,490	0.56	48.63
	Stab Base	PCC	225,000		109,520		51.32	954,752		324.33
	Comp Subgrade	SL	18,065		17,320		4.12	15,766		12.73
R09A	Asphalt	AC	556,267	4.70	150,540	2.55	72.94	371,868	2.57	33.15
	Stab Base	PCC	225,000		398,222		76.99	180,133		19.94
	Comp Subgrade	SL	9,227		11,235		21.76	11,144		20.78
R15A	Asphalt	AC	225,112	7.50	114,600	0.48	49.09	113,424	0.48	49.61
	Stab Base	PCC	101,095		194,614		92.51	196,136		94.01
	Comp Subgrade	SL	17,488		16,139		7.71	16,135		7.74
A511										
A05B	Asphalt	AC	445,950	1.30	1,721,703	0.15	286.08	7,649,881	0.22	1615.41
	HQ Stab Base	PCC	10,581,681		23,199,338		119.24	9,026,641		14.70
	Natural Subgrade	CL	19,303		13,564		29.73	13,603		29.53
A15B	Asphalt	AC	424,161	0.60	522,411	0.07	23.16	878,503	0.12	107.12
	HQ Stab Base	PCC	3,442,336		2,993,083		13.05	2,014,668		41.47
	Natural Subgrade	CL	11,696		11,713		0.15	11,750		0.46
T09B	Asphalt	AC	884,141	0.60	900,440	0.05	1.84	1,116,027	0.05	26.23
	HQ Stab Base	PCC	3,000,784		2,906,020		3.16	2,442,219		18.61
	Natural Subgrade	CL	13,500		13,565		0.48	13,551		0.38

[a] Expert results reported during most recent pavement evaluation using expert seed moduli.

[b] % Error is the error reported by WESDEF.

[c] Using same seed moduli as used in WESDEF for expert results.

[d] RMS reported by BAKFAA.

[e] Between WESDEF expert and BAKFAA results.

[f] Using typical seed moduli recommended in BAKFAA help menu (FAA 2012).

Table 20. Comparison of ELMOD6 and expert results.

Section	Layer	Material Type	Backcalculated Layer Moduli, psi								
			WESDEF Expert Method		ELMOD6 Results						
					Inexperienced User Method				Experienced User Method		
			WESDEF Results[a]	% Error[b]	Mean[c]	% Diff.[d]	Representative Basin[e]	% Diff.[d]	LET[f]	RMS[g],mils	% Diff.[d]
Pope Field											
R01A	PCC	PCC	4,406,326	0.90	2,977,300	32.43	3,038,600	31.04	2,501,800	0.89	43.22
	Base	Sand	46,672		27,400	41.29	62,600	34.13	70,700		51.48
	Natural Subgrade	SM	26,813		29,100	8.53	27,500	2.56	24,000		10.49
A27B	PCC	PCC	7,303,390	2.40	6,144,200	15.87	5,413,600	25.88	7,247,300	0.43	0.77
	HQ Stab Base	Macadam	3,312,134		1,400	99.96	1,300	99.96	1,594,500		51.86
	Comp Subgrade	SW-SM	12,870		33,500	160.30	34,200	165.73	22,000		70.94
T05A	PCC	PCC	4,309,366	0.50	5,086,100	18.02	5,049,100	17.17	10,000,000	1.68	132.05
	Base	GW	1,769,747		11,100	99.37	14,400	99.19	149,900		91.53
	Comp Subgrade	SP-SM	20,637		39,900	93.34	36,300	75.90	28,300		37.13
T23C	Asphalt	AC	1,580,224	1.70	1,107,400	29.92	1,081,400	31.57	999,900	1.68	36.72
	Base	GW-GM	41,627		40,500	2.71	43,800	5.22	66,800		60.47
	Natural Subgrade	SW-SM	16,553		23,300	40.76	16,800	1.49	14,000		15.42
A21B	Asphalt	AC	650,714	0.70	548,500	15.71	383,000	41.14	9,555,500	1.05	1,368.46
	Base	GP-GM	41,036		59,100	44.02	50,900	24.04	26,200		36.15
	Subbase	SC	25,605		33,000	28.88	34,200	33.57	30,300		18.34
	Natural Subgrade	SC	16,891		12,000	28.96	10,900	35.47	23,300		37.94
R09C2	Asphalt	AC	1,045,359	2.20	830,100	20.59	743,400	28.89	1,535,200	0.53	46.86
	Base	GP-GM	226,795		574,600	153.36	445,100	96.26	173,500		23.50
	Comp Subgrade	SM	22,079		21,300	3.53	18,500	16.21	29,000		31.35

Section	Layer	Material Type	Backcalculated Layer Moduli, psi								
			WESDEF Expert Method		ELMOD6 Results						
					Inexperienced User Method				Experienced User Method		
			WESDEF Results[a]	% Error[b]	Mean[c]	% Diff.[d]	Representative Basin[e]	% Diff.[d]	LET[f]	RMS[g],mils	% Diff.[d]
	Asphalt	AC	526,588		450,000	14.54	705,300	33.94	655,000		24.39
	HQ Stab Base	PCC	4,877,044	2.60	4,486,400	8.01	6,505,200	33.38	2,476,400	0.85	49.22
A14B	Comp Subgrade	SM	16,600		12,200	26.51	9,000	45.78	21,600		30.12
	Asphalt	AC	535,532		374,100	30.14	277,200	48.24	181,400		66.13
	HQ Stab Base	PCC	3,707,517	2.00	6,340,800	71.03	11,468,400	209.33	506,400	1.75	86.34
A16B1	Comp Subgrade	SC	22,863		12,700	44.45	10,500	54.07	18,300		19.96
	Asphalt	AC	1,287,990		165,500	87.15	198,800	84.57	356,700		72.31
	HQ Stab Base	PCC	211,083	3.70	1,796,700	751.18	1,790,400	748.20	500,400	2.68	137.06
A16B2	Comp Subgrade	SC	15,948		12,000	24.76	12,800	19.74	28,900		81.21
Campbell AAF											
	PCC	PCC	5,551,901	1.40	5,003,100	9.88	6,314,300	13.73	2,501,300	1.52	54.95
A22B	Natural Subgrade	CL	12,702		7,600	40.17	6,800	46.47	14,700		15.73
	PCC	PCC	5,837,475	2.10	5,945,300	1.85	6,813,100	16.71	2,522,700	0.85	56.78
A14B	Natural Subgrade	CL	21,225		10,900	48.65	10,600	50.06	21,300		0.35
	PCC	PCC	7,295,389		6,646,100	8.90	6,900,600	5.41	9,999,700		37.07
	Base	GW	63,831	0.80	2,900	95.46	2,900	95.46	149,400	2.7	134.06
T02A	Comp Subgrade	CL	14,514		23,000	58.47	25,500	75.69	21,300		46.75
	Asphalt	AC	274,665		274,900	0.09	290,600	5.80	224,400		18.30
	Base	GW	14,405	11.10	24,000	66.61	16,800	16.63	7,200	0.13	50.02
R10A	Natural Subgrade	CL	26,938		13,700	49.14	20,900	22.41	28,100		4.31

Section	Layer	Material Type	Backcalculated Layer Moduli, psi								
			WESDEF Expert Method		ELMOD6 Results						
					Inexperienced User Method				Experienced User Method		
			WESDEF Results[a]	% Error[b]	Mean[c]	% Diff.[d]	Representative Basin[e]	% Diff.[d]	LET[f]	RMS[g],mils	% Diff.[d]
T16C	Asphalt	AC	311,323	0.70	308,700	0.84	257,900	17.16	396,100	0.54	27.23
	Base	GW	53,052		53,500	0.84	55,500	4.61	41,900		21.02
	Subbase	Dense Graded Aggregate	16,333		29,300	79.39	27,000	65.31	15,200		6.94
	Natural Subgrade	CL	23,270		14,700	36.83	14,400	38.12	32,600		40.09
T07C	Asphalt	AC	314,437	1.50	343,400	9.21	268,000	14.77	384,900	1.83	22.41
	Base	Water-Bound Macadam	73,448		94,200	28.25	84,100	14.50	150,000		104.23
	Subbase	GW	32,870		51,100	55.46	45,600	38.73	150,000		356.34
	Comp Subgrade	CL	28,847		22,700	21.31	25,000	13.34	38,000		31.73
R01A	Asphalt	AC	607,490	1.10	485,200	20.13	604,100	0.56	144,200	5.07	76.26
	HQ Stab Base	PCC	4,200,487		2,436,600	41.99	2,172,600	48.28	500,000		88.10
	Natural Subgrade	CL	27,740		49,100	77.00	57,100	105.84	23,400		15.65
Biggs AAF											
A03B	PCC	PCC	8,681,409	0.80	3,789,000	56.36	4,507,700	48.08	15,692,400	0.59	80.76
	Comp Subgrade	SM-SC	24,148		42,300	75.17	42,700	76.83	32,500		34.59
A26B	PCC	PCC	6,312,345	1.50	3,372,500	46.57	3,112,400	50.69	5,526,900	0.22	12.44
	Comp Subgrade	SM	29,609		35,600	20.23	40,500	36.78	38,200		29.01
R03A	PCC	PCC	9,120,589	0.80	5,272,500	42.19	5,473,200	39.99	22,688,100	0.34	148.76
	Comp Subgrade	SM-SC	20,473		52,000	153.99	45,400	121.76	45,100		120.29

Section	Layer	Material Type	Backcalculated Layer Moduli, psi								
			WESDEF Expert Method		ELMOD6 Results						
					Inexperienced User Method				Experienced User Method		
			WESDEF Results[a]	% Error[b]	Mean[c]	% Diff.[d]	Representative Basin[e]	% Diff.[d]	LET[f]	RMS[g], mils	% Diff.[d]
T16A	PCC	PCC	9,214,213	0.50	4,973,100	46.03	5,896,600	36.01	9,997,400	1.73	8.50
	Comp Subgrade	SM-SC	18,593		45,000	142.03	42,100	126.43	30,700		65.12
T20B	Asphalt	AC	950,941	11.80	645,400	32.13	766,100	19.44	827,300	0.97	13.00
	Base	Clayey Sandy Gravel	39,977		30,300	24.21	42,900	7.31	45,400		13.57
	Comp Subgrade	SM	27,485		28,000	1.87	27,200	1.04	30,000		9.15
Wheeler Sack AAF											
R11A	Asphalt	AC	999,991	2.50	992,000	0.80	1,016,500	1.65	1,215,000	0.54	21.50
	Base	Aggregate Base	166,307		90,600	45.52	76,500	54.00	51,500		69.03
	Natural Subgrade	SP	16,670		19,200	15.18	21,100	26.57	19,700		18.18
T02A	Asphalt	AC	597,265	3.40	682,200	14.22	731,500	22.47	949,300	0.91	58.94
	Base	Granular Base	129,726		85,200	34.32	82,200	36.64	74,900		42.26
	Natural Subgrade	SP	21,310		24,000	12.62	25,400	19.19	24,000		12.62
T21B	Asphalt	AC	488,230	3.00	633,500	29.75	603,000	23.51	507,400	1.54	3.93
	Base	Granular Base	99,839		58,000	41.91	63,300	36.60	85,300		14.56
	Natural Subgrade	SP	18,395		23,000	25.03	21,500	16.88	25,000		35.91
Phillips AAF											
R11A	Asphalt	AC	55,465	13.50	44,800	19.23	n/a	n/a	50,000	1.2	9.85
	Stab Base	PCC	225,000		876,000	289.33	n/a	n/a	225,000		0.00
	Comp Subgrade	SL	18,065		6,700	62.91	n/a	n/a	19,600		8.50

Section	Layer	Material Type	Backcalculated Layer Moduli, psi								
			WESDEF Expert Method		ELMOD6 Results						
					Inexperienced User Method				Experienced User Method		
			WESDEF Results[a]	% Error[b]	Mean[c]	% Diff.[d]	Representative Basin[e]	% Diff.[d]	LET[f]	RMS[g],mils	% Diff.[d]
R09A	Asphalt	AC	556,267	4.70	52,100	90.63	n/a	n/a	30,000	6.13	94.61
	Stab Base	PCC	225,000		1,042,800	363.47	n/a	n/a	225,000		0.00
	Comp Subgrade	SL	9,227		3,300	64.24	n/a	n/a	7,700		16.55
R15A	Asphalt	AC	225,112	7.50	82,100	63.53	n/a	n/a	89,200	1.11	60.38
	Stab Base	PCC	101,095		451,700	346.81	n/a	n/a	180,500		78.54
	Comp Subgrade	SL	17,488		8,900	49.11	n/a	n/a	19,000		8.65

Note: A511's HWD files were not compatible with ELMOD6; thus, results could not be obtained.

[a] Expert results reported during most recent pavement evaluation using expert seed moduli.

[b] % Error is the error reported by WESDEF.

[c] Mean moduli for all basins reported by ELMOD6.

[d] Between WESDEF and ELMOD6 results.

[e] Moduli for representative basin reported in WESDEF.

[f] Moduli using LET program.

[g] RMS reported only for LET program results.

5.2 Reasonableness or accuracy of backcalculated moduli

The reasonableness of the backcalculated moduli were then investigated by comparing the backcalculated results for each section from the three programs to established ranges for the material types. The reasonable moduli ranges were gleaned from the program defaults presented in Chapter 4 or program literature and are summarized in Table 21. This table also contains values provided by Stubstad et al. (2006b) presented in Chapter 2, as they provided ranges for various base and subbase materials in lieu of lumping them into broad categories of base or subbase materials. The values in the table show that there are varying opinions on acceptable moduli ranges for the same pavement layers.

Using the minimum and maximum moduli values in Table 21, the acceptable ranges of moduli were determined to be

- AC surface 70,000 to 3,625,000 psi
- PCC surface 1,000,000 to 10,150,000 psi
- Granular base (generic) 5,000 to 217,500 psi
- Asphalt treated base 100,000 to 3,625,000 psi
- High-quality stabilized base 200,000 to 2,500,000 psi
- Stabilized base 10,000 to 1,000,000 psi
- Lean concrete base 22,000 to 3,000,000 psi
- PCC base slab 2,500,000 to 10,000,000 psi
- Subbase 5,000 to 150,000 psi
- Subgrade: 1,000 to 94,250 psi

Of these values, it may be unreasonable to obtain subgrade moduli as high as 95,000 psi. For PCC base slabs, the minimum moduli of 2,500,000 may be too high for severely deteriorated slabs, and the minimum used for PCC surface of 1,000,000 psi was considered more suitable. The current USAF and Army practice is to set a maximum of 30,000 psi for subgrade materials, and if the backcalculated moduli are higher than this, one must determine if there is bedrock beneath the pavement. For determining whether the moduli backcalculated were reasonable, the following ranges were then used:

- AC surface 70,000 to 3,625,000 psi
- PCC surface 1,000,000 to 10,150,000 psi
- Granular base (generic) 5,000 to 220,000 psi
- Asphalt treated base 100,000 to 3,625,000 psi

• High-quality stabilized base	200,000 to 5,000,000 psi
• PCC base slab	1,000,000 to 10,000,000 psi
• Stabilized base	10,000 to 1,000,000 psi
• Lean concrete base	22,000 to 3,000,000 psi
• Subbase	5,000 to 150,000 psi
• Subgrade	1,000 to 30,000 psi

5.2.1 WESDEF

The results in Table 18 show that an inexperienced user can obtain reasonable results for PCC pavements conducting the backcalculation analyses with the software set to analyze either inside or outside the modulus limits without adjusting the seed moduli. For most PCC sections analyzed, the percent difference between the modulus values obtained allowing the backcalculation analyses to be performed outside the limits and the expert values were low (0 to 12 percent). Higher differences were noted between the expert values and the modulus values obtained with the backcalculation analyses forced to remain within the limits. Regardless of adjusting the moduli or conducting the backcalculation analyses inside or outside of the limits, low percent errors (<3 percent) were obtained for the majority of the modulus results, indicating that the pavement models used for backcalculation were adequate for determining moduli for rigid pavements.

The results in Table 18 also show that an inexperienced user can obtain reasonable results for the evaluated AC pavement sections by conducting the backcalculation analyses both inside and outside the modulus limits with no adjustment of the seed moduli. Some exceptions were R10A for Campbell AAF that had a relatively weak base (<15,000 psi). Another exception was R09C2 at Pope Field, where the base strength was high (>220,000 psi). Higher errors were obtained for these pavement sections (>3 percent).

The greatest variation between WESDEF results was experienced when evaluating composite pavements. These were evaluated as AC over high-quality stabilized base materials, following the Army method. For most composite sections analyzed, high percent differences between the expert and inexperienced user results were noted, and higher percent errors were reported compared to PCC or AC pavements regardless of method of analysis. Despite these differences and high percent errors, most layer modulus results were considered reasonable when compared to the values listed in this section. Exceptions were sections A05B at A511, where the PCC base was predicted to be over 10,000,000 psi, and R11A at Phillips AAF, which had a thin AC layer (3.5 in.). R11A also had only two test points (basins) for backcalculation, which can make backcalculation difficult. Since this pavement was last evaluated in 2010, it has been recommended to have at least five test points per pavement feature.

The high percent errors obtained for the composite sections indicated that the results provided by WESDEF might not accurately represent the stiffness of pavement structure. Because of this, the backcalculation process was repeated using the PCC base slab option (following the Air Force method) instead of a high-quality stabilized base. The results of these analyses are presented in Table 22. As shown in this table, for many of the composite pavements (A14B, A16B1, R01A, A05B, A15B, and T09B), similar modulus results were obtained analyzing the system as a PCC base slab or as a high-quality stabilized base, using either the expert or inexperienced user methods. For Sections A16B2, R11A, R09A, and R15A, more varied results were obtained, along with high percent errors (>3 percent). Additional analyses are needed to determine which method is the most suitable for evaluation purposes.

For most of the pavement sections evaluated, the inexperienced user method of analyzing the system outside the limits provided reasonable results that were similar to the expert results. Comparing these results to those with the limits turned on and to acceptable moduli ranges identified sections that required further investigation, such as looking at DCP data or consulting a previous report for additional data. For example, the base strength predicted for T05A at Pope Field when analyzing the pavement structure outside the limits was approximately 1,800,000 psi. This is much higher than the typical maximum modulus of 150,000 psi for a base material. Additional information about the pavement base material was needed to determine whether this value was reasonable for the base. Another example is R09C2 at Pope Field, where the base modulus was over 300,000 psi when run outside the limits. Additional sections must be analyzed to determine whether there are any pavement section types (besides composite sections) that may cause an inexperienced user problems when backcalculating.

Table 21. Comparison of acceptable moduli ranges and initial seed moduli.

Material	WESDEF[a]			BAKFAA[b]			ELMOD6[c]			Stubstad et al. 2006b		
	Modulus range		Initial seed	Modulus range		Initial seed	Modulus range		Initial seed	Modulus range		Initial seed
	Minimum	Maximum		Minimum	Maximum		Minimum	Maximum		Minimum	Maximum	
	psi	psi	psi	psi	psi	psi	psi	psi	psi	psi	psi	psi
AC surface	100,000	1,000,000	350,000	70,000	2,000,000	500,000	400,000	1,000,000	--	101,500	3,625,000	--
PCC surface	2,500,000	10,000,000	5,000,000	1,000,000	9,000,000	5,000,000	3,000,000	6,000,000	--	1,450,000	10,150,000	--
Granular base (generic)	5,000	150,000	61,000	10,000	50,000	30,000	15,000	150,000	--	--	--	--
Uncrushed gravel	--	--	--	--	--	--	--	--	--	7,250	108,750	--
Crushed stone	--	--	--	--	--	--	--	--	--	14,500	217,500	--
Crushed gravel	--	--	--	--	--	--	--	--	--	10,875	145,000	--
Sand	--	--	--	--	--	--	--	--	--	5,800	72,500	--
Soil-aggregate mixture (predominantly fine-grained)	--	--	--	--	--	--	--	--	--	7,250	101,500	--
Soil-aggregate mixture (predominantly coarse-grained)	--	--	--	--	--	--	--	--	--	8,700	116,000	--
Nonpermeable asphalt treated base	--	--	--	100,000	1,500,000	500,000	--	--	--	101,500	3,625,000	--
High-quality stabilized base	500,000	2,500,000	1,000,000	200,000	2,000,000	750,000	--	--	--	290,000	2,900,000	--
Stabilized base	100,000	1,000,000	300,000	10,000	200,000	50,000	--	--	--	--	--	--
Lean concrete base	--	--	--	1,000,000	3,000,000	2,000,000	1,500,000	2,500,000	--	21,750	217,500	--
PCC base slabs	2,500,000	10,000,000	5,000,000	--	--	--	--	--	--	--	--	--
Unstabilized subbase	5,000	150,000	24,000	5,000	30,000	15,000	15,000	150,000	--	--	--	--
Subgrade	1,000	50,000	15,000	3,000	25,000	7,000	5,000	50,000	--	2,175	94,250	--

Note: Dashed cells, information not provided

[a] Defaults in PCASE

[b] Provided in BAKFAA help menu

[c] From ELMOD6 ERDC training guide (2014), provided by Dynatest

Table 22. Comparison of WESDEF composite pavement modulus results.

Section	Material Type	Backcalculated Layer Moduli, psi											
		PCC Analyzed as HQ Stabilized Base						PCC Analyzed as PCC Base Slab					
		Expert		Inexperienced User				Expert		Inexperienced User			
		Expert Results	% Error	Limits On	% Error	Limits Off	% Error	Expert Results	% Error	Limits On	% Error	Limits Off	% Error
Pope Field													
	AC	526,588		603,625		620,661		948,775		529,619		1,089,927	
	PCC	4,877,044	2.60	4,355,680	2.60	4,113,237	2.70	6,076,444	0.60	4,766,914	1.90	4,986,688	0.80
A14B	SM	16,600		16,635		16,657		18,635		16,148		18,686	
	AC	535,532		573,855		479,288		522,862		504,753		1,208,697	
	PCC	3,707,517	2.00	3,464,625	1.90	3,725,312	2.50	4,183,352	1.80	4,274,967	1.80	3,382,669	5.90
A16B1	SC	22,863		22,907		22,865		23,077		23,052		18,723	
	AC	1,287,990		369,115		1,287,980		510,121		118,306		510,121	
	PCC	211,083	3.70	500,000	11.50	211,089	3.70	684,058	2.80	2,500,000	12.30	684,058	2.80
A16B2	SC	15,948		18,895		15,948		16,284		18,895		16,284	
Campbell AAF													
	AC	607,490		603,410		607,506		606,100		604,822		605,702	
	PCC	4,200,487	1.10	4,218,993	1.10	4,199,773	1.10	4,394,263	1.10	4,402,021	1.10	4,394,311	1.10
R01A	CL	27,740		27,750		27,739		28,062		28,060		28,065	
Phillips AAF													
	AC	55,465		28,579		1,344,817		29,583		100,000		100,000	
	PCC	225,000	13.50	712,999	14.60	146,070	3.30	750,678	13.90	2,500,000	28.90	2,500,000	13.90
R11A	SL	18,065		16,755		16,585		17,007		2,566		2,566	
	AC	556,267		100,000		74,981		72,945		100,000		100,000	
	PCC	225,000	4.70	1,000,000	2.90	1,539,875	1.70	1,713,532	1.60	2,500,000	7.70	2,500,000	1.60
R09A	SL	9,227		8,927		9,292		9,361		8,702		8,702	
	AC	225,112		811,063		2,672,129		1,667,117		100,000		100,000	
	PCC	101,095	7.50	49,312	7.70	14,359	5.00	42,854		2,500,000	29.60	2,500,000	6.60
R15A	SL	17,488		16,736		18,143		17,600		16,080		16,080	

Section	Material Type	Backcalculated Layer Moduli, psi											
		PCC Analyzed as HQ Stabilized Base						PCC Analyzed as PCC Base Slab					
		Expert		Inexperienced User				Expert		Inexperienced User			
		Expert Results	% Error	Limits On	% Error	Limits Off	% Error	Expert Results	% Error	Limits On	% Error	Limits Off	% Error
A511													
	AC	445,950		445,198		746,746		434,774		501,368		743,053	
	PCC	10,581,681	1.30	10,587,054	1.30	10,000,000	27.70	11,024,141	1.30	10,000,000	1.30	10,000,000	28.60
A05B	CL	19,303		19,302		13,817		19,433		19,785		13,907	
	AC	424,161		424,161		338,678		462,647		462,647		462,021	
	PCC	3,442,336	0.60	3,442,336	0.60	4,276,992	1.40	3,386,582	0.60	3,386,582	0.60	3,390,251	0.60
A15B	CL	11,696		11,696		10,913		11,786		11,786		11,784	
	AC	884,141		884,141		2,414,290		898,753		784,733		779,783	
	PCC	3,000,784	0.60	3,000,784	0.60	1,319,288	0.50	3,124,828	0.70	3,387,691	0.60	3,401,832	0.60
T09B	CL	13,500		13,500		13,373		13,647		13,683		13,683	

Table 23. Comparison of backcalculated modulus results for all programs.

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			WESDEF Results			BAKFAA Results		ELMOD6 Results		
				Inexperienced User Results						
			Expert Results	Limits On	Limits Off	Expert Seed	Typical Seed	Mean	Representative Basin	LET
Pope Field										
	PCC	PCC	4,406,326	4,058,277	4,406,326	4,503,865	4,496,294	2,977,300	3,038,600	2,501,800
	Base	Sand	46,672	39,257	46,672	33,455	33,810	27,400	62,600	70,700
R01A	Natural Subgrade	SM	26,813	22,082	26,813	27,089	27,045	29,100	27,500	24,000
	PCC	PCC	7,303,390	7,892,199	7,303,390	7,549,188	7,449,287	6,144,200	5,413,600	7,247,300
	HQ Stab Base	Macadam	3,312,134	4,011,167	3,312,134	945,777	1,080,609	1,400	1,300	1,594,500
A27B	Comp Subgrade	SW-SM	12,870	15,336	12,870	12,707	12,693	33,500	34,200	22,000
	PCC	PCC	4,309,366	6,282,110	4,309,366	6,084,615	6,217,408	5,086,100	5,049,100	10,000,000
	Base	GW	1,769,747	150,000	1,769,747	66,749	35,207	11,100	14,400	149,900
T05A	Comp Subgrade	SP-SM	20,637	23,568	20,637	21,810	22,182	39,900	36,300	28,300
	Asphalt	AC	1,580,224	1,581,671	1,580,224	1,425,258	1,425,367	1,107,400	1,081,400	999,900
	Base	GW-GM	41,627	41,601	41,627	43,588	43,582	40,500	43,800	66,800
T23C	Natural Subgrade	SW-SM	16,553	16,558	16,553	16,506	16,508	23,300	16,800	14,000
	Asphalt	AC	650,714	650,714	638,519	635,790	635,908	548,500	383,000	9,555,500
	Base	GP-GM	41,036	41,036	41,744	38,566	38,546	59,100	50,900	26,200
	Subbase	SC	25,605	25,605	26,436	26,127	26,135	33,000	34,200	30,300
A21B	Natural Subgrade	SC	16,891	16,891	16,856	16,879	16,877	12,000	10,900	23,300
	Asphalt	AC	1,045,359	1,000,000	1,000,795	1,112,611	1,156,646	830,100	743,400	1,535,200
	Base	GP-GM	226,795	150,000	306,348	127,804	110,441	574,600	445,100	173,500
R09C2	Comp Subgrade	SM	22,079	26,490	25,112	22,196	22,262	21,300	18,500	29,000

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			WESDEF Results			BAKFAA Results		ELMOD6 Results		
				Inexperienced User Results						
			Expert Results	Limits On	Limits Off	Expert Seed	Typical Seed	Mean	Representative Basin	LET
	Asphalt	AC	526,588	603,625	620,661	1,124,136	1,134,431	450,000	705,300	655,000
	HQ Stab Base	PCC	4,877,044	4,355,680	4,113,237	2,576,122	2,553,072	4,486,400	**6,505,200**	2,476,400
A14B	Comp Subgrade	SM	16,600	16,635	16,657	16,389	16,381	12,200	9,000	21,600
	Asphalt	AC	535,532	573,855	479,288	539,656	916,336	374,100	277,200	181,400
	HQ Stab Base	PCC	3,707,517	3,464,625	3,725,312	3,925,293	1,975,645	**6,340,800**	**11,468,400**	506,400
A16B1	Comp Subgrade	SC	22,863	22,907	22,865	22,641	22,639	12,700	10,500	18,300
	Asphalt	AC	1,287,990	369,115	1,287,980	875,958	1,084,827	165,500	198,800	356,700
	HQ Stab Base	PCC	211,083	500,000	211,089	339,787	290,470	1,796,700	1,790,400	500,400
A16B2	Comp Subgrade	SC	15,948	18,895	15,948	16,126	16,113	12,000	12,800	28,900
Campbell AAF										
	PCC	PCC	5,551,901	5,539,264	5,544,004	5,501,352	5,504,092	5,003,100	6,314,300	2,501,300
A22B	Natural Subgrade	CL	12,702	12,709	12,707	12,512	12,509	7,600	6,800	14,700
	PCC	PCC	5,837,475	5,832,900	5,836,234	5,674,756	5,673,704	5,945,300	6,813,100	2,522,700
A14B	Natural Subgrade	CL	21,225	21,232	21,227	20,806	20,808	10,900	10,600	21,300
	PCC	PCC	7,295,389	7,295,389	7,295,389	6,928,318	6,787,162	6,646,100	6,900,600	**9,999,700**
	Base	GW	63,831	63,831	63,831	40,263	51,577	**2,900**	**2,900**	149,400
T02A	Comp Subgrade	CL	14,514	14,514	14,514	14,892	14,687	23,000	25,500	21,300
	Asphalt	AC	274,665	300,650	300,303	333,214	332,342	274,900	290,600	224,400
	Base	GW	14,405	11,588	11,585	13,503	13,558	24,000	16,800	7,200
R10A	Natural Subgrade	CL	26,938	26,648	26,649	27,729	27,674	13,700	20,900	28,100

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			WESDEF Results			BAKFAA Results		ELMOD6 Results		
				Inexperienced User Results						
			Expert Results	Limits On	Limits Off	Expert Seed	Typical Seed	Mean	Representative Basin	LET
	Asphalt	AC	311,323	311,323	311,348	302,810	523,625	308,700	257,900	396,100
	Base	GW	53,052	53,052	52,919	55,922	52,418	53,500	55,500	41,900
	Subbase	Dense Graded Aggregate	16,333	16,333	16,412	15,991	7,919	29,300	27,000	15,200
T16C	Natural Subgrade	CL	23,270	23,270	23,353	23,443	21,558	14,700	14,400	**32,600**
	Asphalt	AC	314,437	314,437	315,470	304,844	307,518	343,400	268,000	384,900
	Base	Water-Bound Macadam	73,448	73,448	73,081	79,103	78,014	94,200	84,100	150,000
	Subbase	GW	32,870	32,870	32,934	30,968	31,255	51,100	45,600	150,000
T07C	Comp Subgrade	CL	28,847	28,847	28,832	29,314	29,260	22,700	25,000	**38,000**
	Asphalt	AC	607,490	603,410	607,506	616,587	615,772	485,200	604,100	144,200
	HQ Stab Base	PCC	4,200,487	4,218,993	4,199,773	4,238,198	4,256,020	2,436,600	2,172,600	500,000
R01A	Natural Subgrade	CL	27,740	27,750	27,739	27,518	27,502	**49,100**	**57,100**	23,400
Biggs AAF										
	PCC	PCC	8,681,409	6,161,896	8,743,264	8,429,208	8,426,667	3,789,000	4,507,700	**15,692,400**
A03B	Comp Subgrade	SM-SC	24,148	22,470	23,897	23,898	23,903	**42,300**	**42,700**	**32,500**
	PCC	PCC	6,312,345	6,315,491	6,318,388	5,884,091	5,882,253	3,372,500	3,112,400	5,526,900
A26B	Comp Subgrade	SM	29,609	29,569	29,634	29,627	29,627	**35,600**	**40,500**	**38,200**
	PCC	PCC	9,120,589	6,683,451	8,036,184	9,368,471	9,353,244	5,272,500	5,473,200	**22,688,100**
R03A	Comp Subgrade	SM-SC	20,473	**35,141**	21,263	19,659	19,687	**52,000**	**45,400**	**45,100**

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			WESDEF Results			BAKFAA Results		ELMOD6 Results		
				Inexperienced User Results						
Section	Layer	Material Type	Expert Results	Limits On	Limits Off	Expert Seed	Typical Seed	Mean	Representative Basin	LET
	PCC	PCC	9,214,213	8,397,435	9,255,958	8,914,572	8,918,771	4,973,100	5,896,600	9,997,400
T16A	Comp Subgrade	SM-SC	18,593	21,228	18,587	18,625	18,621	**45,000**	**42,100**	**30,700**
	Asphalt	AC	950,941	252,904	947,263	962,516	959,884	645,400	766,100	827,300
	Base	Clayey Sandy Gravel	39,977	31,353	40,124	38,862	38,917	30,300	42,900	45,400
T20B	Comp Subgrade	SM	27,485	22,145	27,483	28,233	28,222	28,000	27,200	30,000
Wheeler Sack AAF										
	Asphalt	AC	999,991	1,000,000	1,344,817	1,067,223	1,069,594	992,000	1,016,500	1,215,000
	Base	Aggregate Base	166,307	167,468	146,070	145,285	145,071	90,600	76,500	51,500
R11A	Natural Subgrade	SP	16,670	16,226	16,585	16,864	16,858	19,200	21,100	19,700
	Asphalt	AC	597,265	677,133	607,952	788,199	783,608	682,200	731,500	949,300
	Base	Granular Base	129,726	112,553	128,211	106,109	106,878	85,200	82,200	74,900
T02A	Natural Subgrade	SP	21,310	19,435	21,312	21,588	21,575	24,000	25,400	24,000
	Asphalt	AC	488,230	488,075	558,773	645,372	645,092	633,500	603,000	507,400
	Base	Granular Base	99,839	99,845	90,745	81,131	81,085	58,000	63,300	85,300
T21B	Natural Subgrade	SP	18,395	18,395	19,795	18,515	18,516	23,000	21,500	25,000
Phillips AAF										
	Asphalt	AC	**55,465**	**28,579**	1,344,817	108,368	**28,490**	**44,800**	—[a]	**50,000**
	Stab Base	PCC	225,000	712,999	146,070	109,520	954,752	876,000	—[a]	225,000
R11A	Comp Subgrade	SL	18,065	16,755	16,585	17,320	15,766	6,700	—[a]	19,600
	Asphalt	AC	556,267	100,000	74,981	150,540	371,868	**52,100**	—[a]	**30,000**
R09A	Stab Base	PCC	225,000	1,000,000	**1,539,875**	398,222	180,133	**1,042,800**	—[a]	225,000

Section	Layer	Material Type	Backcalculated Layer Moduli, psi							
			WESDEF Results			BAKFAA Results		ELMOD6 Results		
				Inexperienced User Results						
			Expert Results	Limits On	Limits Off	Expert Seed	Typical Seed	Mean	Representative Basin	LET
	Comp Subgrade	SL	9,227	8,927	9,292	11,235	11,144	3,300	—[a]	7,700
R15A	Asphalt	AC	225,112	811,063	2,672,129	114,600	113,424	82,100	—[a]	89,200
	Stab Base	PCC	101,095	49,312	14,359	194,614	196,136	451,700	—[a]	180,500
	Comp Subgrade	SL	17,488	16,736	18,143	16,139	16,135	8,900	—[a]	19,000
A511										
A05B	Asphalt	AC	445,950	445,198	746,746	1,721,703	**7,649,881**	—[b]	—[b]	—[b]
	HQ Stab Base	PCC	**10,581,681**	**10,587,054**	**10,000,000**	**23,199,338**	**9,026,641**	—[b]	—[b]	—[b]
	Natural Subgrade	CL	19,303	19,302	13,817	13,564	13,603	—[b]	—[b]	—[b]
A15B	Asphalt	AC	424,161	424,161	338,678	522,411	878,503	—[b]	—[b]	—[b]
	HQ Stab Base	PCC	3,442,336	3,442,336	4,276,992	2,993,083	2,014,668	—[b]	—[b]	—[b]
	Natural Subgrade	CL	11,696	11,696	10,913	11,713	11,750	—[b]	—[b]	—[b]
T09B	Asphalt	AC	884,141	884,141	2,414,290	900,440	1,116,027	—[b]	—[b]	—[b]
	HQ Stab Base	PCC	3,000,784	3,000,784	1,319,288	2,906,020	2,442,219	—[b]	—[b]	—[b]
	Natural Subgrade	CL	13,500	13,500	13,373	13,565	13,551	—[b]	—[b]	—[b]

Note: Boldfaced moduli were considered unreasonable when compared to the moduli ranges presented in Section 5.2.

[a] The moduli were fixed; therefore, there was no representative basin for this pavement feature.

[b] The HWD files were not compatible with ELMOD6.

In addition to a comparison of the backcalculated moduli to an acceptable range for each material, an examination of the percent error reported for the representative basin should also be made. For the pavement sections analyzed, high percent errors (more than 3 percent) corresponded to pavements that would require review of the pavement layer structure before acceptance or rejection of the modulus results. In most cases, there was a notable difference between the modulus results reported within and outside the modulus limits. This also indicates that further investigation into the pavement structure is required before acceptance or rejection of the modulus results. It is recommended that the percent error for the representative section be moved to the main WESDEF results page so that this error will be easily noticed by the inexperienced user instead of being available only after clicking the **Graph Es** button.

5.2.2 BAKFAA

BAKFAA results are presented in Table 19. For the PCC pavements, BAKFAA provided reasonable modulus results when compared to the acceptable ranges presented previously using both the experienced (using WESDEF expert seed moduli) and inexperienced methods (using the defaults for BAKFAA) (see Table 21 for BAKFAA's seed moduli). Identical results to the WESDEF results could not be obtained even when using the same seed moduli; however, similar values to those backcalculated in WESDEF could be obtained using the default seed modulus values. The inexperienced user results for the PCC pavements were similar to the expert solutions for these sections with one exception, Pope Field's Section T05A, which had notable differences. These results indicate that for the sections evaluated in this study, BAKFAA can be used by an inexperienced user to obtain results similar to the expert results in WESDEF. For Section T05A, much lower moduli were backcalculated for the limestone base, using both the expert seed and the typical seed values. When evaluating stiff base layers beneath PCC pavements, BAKFAA may require more engineering judgment. Additional analyses of PCC pavements are required to determine whether stiff base layers present more of a challenge for either WESDEF or BAKFAA.

For AC pavements, BAKFAA provided reasonable modulus results for most of the pavements, using both expert seed moduli and default values, indicating that an inexperienced user could in most cases obtain reasonable results without using engineering judgment or manipulation of seed moduli. Differences were noted for Pope Field's Section R09C2, where the modulus for the base layer, using both the expert and the default seed moduli, was approximately half that determined using WESDEF. This section was also identified in the WESDEF analysis, showing differences when analyzed inside versus outside the limits. Another difference was noted for Campbell AAF's Section T16B (a four-layer system): when using the default moduli, a higher modulus was reported for the asphalt surface than when using the expert seed moduli. The remaining asphalt sections' moduli were similar to those reported by WESDEF regardless of the seed moduli used. Additional AC sections, particularly thin AC sections and very strong bases or stabilized bases, should be evaluated for further comparison.

Like WESDEF, BAKFAA was challenging when evaluating composite sections, and analyzing the pavement structures using the expert seed moduli did not result in values similar to the WESDEF expert values. Two composite sections had unreasonable values: Phillips AAF's Section R11A for the asphalt surface layer (using the default seed moduli) and A511's Section A05B for the PCC base slab that was determined to be over 20,000,000 psi (using the expert seed moduli). Large differences in the backcalculated moduli were noted for most of the composite sections.

No correlations between the reported RMS error and unreasonable moduli could be determined from this data set. Other backcalculation software report an RMS error in percent form, not mils with recommendations for accepting results as reasonable if less than 3 to 4 percent. Comparing the percent error reported for WESDEF, for some cases, sections with percent errors over 3 percent had RMS errors values approaching 0.35 mils. This generalization could not be applied across the entire dataset, however. For example, R11A with a reasonable moduli set had an RMS error of 1.22 mils while its unreasonable moduli set had an RMS of 0.56. Additional research with a larger data set is therefore required to determine how RMS error from BAKFAA can be used to determine reasonableness or accuracy of data. Additionally, WESDEF could be modified to calculate an RMS error to be consistent with other software.

5.2.3 ELMOD6

For all the pavements analyzed (PCC, AC, or composite), ELMOD6 results (Table 20) did not compare well with the WESDEF expert values. As mentioned previously, ELMOD6 uses a backcalculation procedure different from those used by WESDEF and BAKFAA unless the LET function is used. Overall, very different modulus results were obtained for the pavement sections using the three backcalculation approaches in ELMOD6. Overall, the mean results were very different from either the representative basin results or the LET results. Additionally, compared to WESDEF and BAKFAA, many modulus results were determined to be unacceptable when compared to the acceptable range of moduli for the pavement layer type. The results using the LET function for the subgrade strengths compared well in many cases but poorly in others, despite using the same seed moduli used in WESDEF calculations.

A comparison of the modulus results from all three programs is shown in Table 23. Moduli values in bold type are those that were determined to be unreasonable, as described earlier. Overall, the WESDEF and BAKFAA results were similar for the PCC and AC pavements, but the ELMOD6 were not. This is not surprising, as both WESDEF and ELMOD6 use similar linear elastic subroutines. Another broad generalization that can be gleaned from this table is that none of the programs appear to provide similar backcalculation results for composite pavements.

5.3 Evaluation of alternative methods or benchmarking approaches

Forwardcalculation, the Metha and Roque backcalculation approach, and benchmarking were all evaluated to determine whether these methods could be used to improve the backcalculation process.

5.3.1 Forwardcalculation

The forwardcalculation approach described by Stubstad et al. (2006a,b) utilizing the AREA method was used to compute forwardcalculated moduli. The spreadsheets provided by the FHWA (for AC and PCC sections) were modified to allow for the seven-deflection sensor setup used by the DoD to be used for calculations as opposed to the nine-sensor arrangement for which the spreadsheets were developed. Three-layer systems were forwardcalculated for the pavement systems. For sections with subbases, the subbase and base thicknesses were combined and capped to a maximum of 24 in., as recommended by the developers. Table 24 shows the forwardcalculation results for the AC pavement sections.

Table 24. Forwardcalculation results for AC sections.

Airfield	Section	Forwardcalculated Moduli, psi			Backcalculated Moduli, psi			Ratio Between Forward- and Backcalculated Moduli		
		AC	Base	Subgrade	AC	Base	Subgrade	AC	Base	Subgrade
Pope Field	T23C	1,650,037	52,306	14,553	1,580,224	41,627	16,553	1.0	1.3	0.9
Pope Field	A21B	787,364	48,188	13,407	650,714	41,036	16,891	1.2	1.2	0.8
Pope Field	R09C2	1,451,121	28,235	15,913	1,045,359	226,795	22,079	1.4	0.1	0.7
Campbell AAF	R10A	321,287	33,242	13,715	274,665	14,405	26,938	1.2	2.3	0.5
Campbell AAF	T16C	447,220	42,615	12,871	311,323	53,052	23,270	1.4	0.8	0.6
Campbell AAF	T07C	493,570	75,787	21,086	314,437	73,448	28,847	1.6	1.0	0.7
Biggs AAF	T20B	1,010,491	42,090	17,365	950,941	39,977	27,485	1.1	1.1	0.6
Wheeler Sack AAF	R11A	1,772,454	28,757	13,118	999,991	166,307	16,670	1.8	0.2	0.8
Wheeler Sack AAF	T02A	1,367,847	41,669	17,192	597,265	129,726	21,310	2.3	0.3	0.8
Wheeler Sack AAF	T21B	1,080,866	35,243	14,540	488,230	99,839	18,395	2.2	0.4	0.8

Correspondence	Code	Ratio Range
Acceptable	0	2/3<Ratio≤1.5
Marginal	1	1/2<Ratio≤2 (and not code 0)
Questionable	2	1/3<Ratio≤3 (and not codes 0 or 1)
Unacceptable	3	Ratio≤1/3 or Ratio>3

As mentioned previously, the forwardcalculation approach is best used for screening purposes to evaluate whether backcalculated modulus values are reasonable. Ratios between the forwardcalculated and backcalculated moduli (expert backcalculated moduli previously computed and reported for the respective airfields) for each pavement section were then compared to the reasonableness ratio ranges (acceptable, marginal, questionable, or unacceptable). The colors corresponding to ratios are also shown in Table 24. As can be seen in the table, with the exception of the base layers, the forward- and backcalculated ratios were either acceptable or marginal in reasonableness. Sections T02A and T21B had questionable moduli for the AC layer, unacceptable moduli for the base layers, but acceptable ratios for the subgrade layer. These results indicate that the backcalculated moduli for these sections and or layer system should be reexamined because the results may be unreasonable.

The forward approach was also applied to the PCC sections (Table 25), and ratios were computed in the same manner used for the AC sections. Overall, the ratios for the PCC and subgrade had ratios within the acceptable range with the exception of R03A and T16A, which had subgrade values much higher for those forwardcalculated than for those backcalculated. Overall, the forwardcalculated moduli for the PCC layers were almost one half of the backcalculated values but were considered marginal or acceptable. These results indicate that the subgrade backcalculated values were acceptable and that R03A and T16A may need to be further evaluated for the presence of a rigid layer.

Table 25. Forwardcalculation results for PCC sections.

Airfield	Section	Forwardcalculated Moduli, psi			Backcalculated Moduli, psi			Ratio Between Forward- and Backcalculated Moduli		
		PCC	Base	Sub-grade	PCC	Base	Sub-grade	PCC	Base	Sub-grade
Pope Field	R01A	2,959,717	11,839	31,742	4,406,326	46,672	26,813	0.7	0.3	1.2
Pope Field	A27B	6,204,920	3,102,460	22,181	7,303,390	3,312,134	12,870	0.8	0.9	1.7
Pope Field	T05A	3,496,287	34,963	32,380	4,309,366	1,769,747	20,637	0.8	0.0	1.6
Campbell AAF	A22B	3,693,123		12,418	5,551,901		12,702	0.7		1.0
Campbell AAF	A14B	3,594,630		20,742	5,837,475		21,225	0.6		1.0
Campbell AAF	T02A	5,430,276	36,202	23,343	7,295,389	63,831	14,514	0.7	0.6	1.6
Biggs AAF	A03B	4,676,143		40,752	8,681,409		24,148	0.5		1.7
Biggs AAF	A26B	3,320,392		33,807	6,312,345		29,609	0.5		1.1
Biggs AAF	R03A	4,345,391		50,802	9,120,589		20,473	0.5		2.5
Biggs AAF	T16A	4,807,728		38,320	9,241,213		18,593	0.5		2.1

Correspondence	Code	Ratio Range
Acceptable	0	2/3<Ratio≤1.5
Marginal	1	1/2<Ratio≤2 (and not code 0)
Questionable	2	1/3<Ratio≤3 (and not codes 0 or 1)
Unacceptable	3	Ratio≤1/3 or Ratio>3

No guidance was provided to apply the forward approach to the composite AC over PCC sections; however, the spreadsheet for PCC pavements was used to calculate the subgrade strengths for comparison purposes. As with the previous sections, the ratios between the forward- and backcalculated moduli are considered acceptable or marginal for the subgrades, as shown in Table 26.

Table 26. Forwardcalculation results for composite sections.

Airfield	Section	Forwardcalculated Moduli, psi	Backcalculated Moduli, psi	Ratio Between Forward- and Backcalculated Moduli
		Subgrade	Subgrade	Subgrade
A14B	Pope Field	16,706	16,600	1.0
A16B1	Pope Field	15,402	22,863	1.5
A16B2	Pope Field	11,796	15,948	1.4
R01A	Campbell AAF	55,117	27,740	0.5
R11A	Phillips AAF	15,298	18,065	1.2
R09A	Phillips AAF	6,980	9,227	1.3
R15A	Phillips AAF	10,252	17,488	1.7
A05B	A511	20,078	13,817	0.7
A15B	A511	13,254	11,696	0.9
T09B	A511	15,521	13,373	0.9

Correspondence	Code	Ratio Range
Acceptable	0	2/3<Ratio≤1.5
Marginal	1	1/2<Ratio≤2 (and not code 0)
Questionable	2	1/3<Ratio≤3 (and not codes 0 or 1)
Unacceptable	3	Ratio≤1/3 or Ratio>3

Overall, these results show a good correlation between backcalculated subgrade and forwardcalculated subgrade moduli, and the process was an easy check for reasonableness of subgrade results when conducting backcalculation. This agrees with the Stubstad et al. (2006a,b) conclusions that the approach is best applied to subgrade comparisons and that intermediate layers may be questionable.

5.3.2 Metha and Roque backcalculation approach

The backcalculation approach presented by Metha and Roque (2003) and described previously in Chapter 3 was used with the PCASE software to compare the results using this approach (referred to as Metha in the results tables) to those obtained using the current WESDEF backcalculation approach. Table 27 presents a comparison of the AC backcalculation results using the Metha method with those using WESDEF. Table 28 presents the PCC results, and Table 29 presents the composite results for the Metha approach.

Table 27. Metha approach AC pavements results.

Section	Material	WESDEF 'Expert'	WESDEF Inside Limits	WESDEF Outside Limits	METHA
Pope Field					
T23C	AC	1,580,224	1,581,671	1,580,224	887,500
	GW-GM	41,627	41,601	41,627	68,240
	SW-SM	16,553	16,558	16,553	16,550
A21B	AC	650,714	650,714	638,519	800,554
	GP-GM	41,036	41,036	41,744	38,501
	SC	25,605	25,605	26,436	32,099
	SC	16,891	16,891	16,856	16,891
R09C2	AC	1,045,359	1,000,000	1,000,795	970,662
	GP-GM	226,795	150,000	306,348	43,752
	SM	22,079	26,490	25,112	22,209
Campbell AAF					
R10A	AC	274,665	300,650	300,303	325,164
	GW	14,405	11,588	11,585	14,864
	CL	26,938	26,648	26,649	27,389
T16C	AC	311,323	311,323	311,348	368,101
	GW	53,052	53,052	52,919	53,713
	DG Aggregate	16,333	16,333	16,412	17,917
	CL	23,270	23,270	23,353	23,270
T07C	AC	314,437	314,437	315,470	467,770
	WB Macadam	73,448	73,448	73,081	82,006
	GW	32,870	32,870	32,934	38,829
	CL	28,847	28,847	28,832	28,847
Biggs AAF					
T20B	AC	950,941	252,904	947,263	870,605
	Clayey Sandy Gravel	39,977	31,353	40,124	44,036
	SM	27,485	22,145	27,483	26,719

Section	Material	WESDEF 'Expert'	WESDEF Inside Limits	WESDEF Outside Limits	METHA
Wheeler Sack AAF					
R11A	AC	999,991	1,000,000	1,344,817	965,552
	Aggregate Base	166,307	167,468	146,070	194,246
	SP	16,670	16,226	16,585	16,192
T02A	AC	597,265	677,133	607,952	678,023
	Granular Base	129,726	112,553	128,211	131,036
	SP	21,310	19,435	21,312	22,401
T21B	AC	488,230	488,075	558,773	623,619
	Granular Base	99,839	99,845	90,745	83,462
	SP	18,395	18,395	19,795	18,395

Table 28. Metha approach rigid pavements results.

Section	Material	WESDEF 'Expert'	WESDEF Inside Limits	WESDEF Outside Limits	METHA
Pope Field					
R01A	PCC	4,406,326	4,058,277	4,406,326	4,508,509
	Sand	46,672	39,257	46,672	31,357
	SM	26,813	22,082	26,813	22,802
A27B	PCC	7,303,390	7,892,199	7,303,390	9,539,984
	Macadam	3,312,134	4,011,167	3,312,134	3,024,745
	SW-SM	12,870	15,336	12,870	15,317
T05A	PCC	4,309,366	6,282,110	4,309,366	7,430,207
	GW	1,769,747	150,000	1,769,747	53,515
	SP-SM	20,637	23,568	20,637	22,153
Campbell AAF					
A22B	PCC	5,551,901	5,539,264	5,544,004	5,478,269
	CL	12,702	12,709	12,707	12,709
A14B	PCC	5,837,475	5,832,900	5,836,234	5,259,729
	CL	21,225	21,232	21,227	21,232
T02A	PCC	7,295,389	7,295,389	7,295,389	6,972,394
	GW	63,831	63,831	63,831	77,313
	CL	14,514	14,514	14,514	14,514
Biggs AAF					
A03B	PCC	8,681,409	6,161,896	8,743,264	5,607,613
	SM-SC	24,148	22,470	23,897	30,652
A26B	PCC	6,312,345	6,315,491	6,318,388	6,076,543
	SM	29,609	29,569	29,634	28,948

Section	Material	WESDEF 'Expert'	WESDEF Inside Limits	WESDEF Outside Limits	METHA
R03A	PCC	9,120,589	6,683,451	8,036,184	9,006,232
	SM-SC	20,473	35,141	21,263	21,263
T16A	PCC	9,214,213	8,397,435	9,255,958	8,442,051
	SM-SC	18,593	21,228	18,587	18,946

Table 29. Metha approach composite pavements results.

Section	Material	WESDEF 'expert'	WESDEF inside limits	WESDEF outside limits	METHA
Pope Field					
A14B	AC	526,588	603,625	620,661	517,531
	PCC	4,877,044	4,355,680	4,113,237	4,091,348
	SM	16,600	16,635	16,657	16,582
A16B1	AC	535,532	573,855	479,288	421,423
	PCC	3,707,517	3,464,625	3,725,312	4,708,094
	SC	22,863	22,907	22,865	22,907
A16B2	AC	1,287,990	369,115	1,287,980	260,164
	PCC	211,083	500,000	211,089	390,541
	SC	15,948	18,895	15,948	15,650
Campbell AAF					
R01A	AC	607,490	603,410	607,506	527,508
	PCC	4,200,487	4,218,993	4,199,773	7,474,762
	CL	27,740	27,750	27,739	31,988
Phillips AAF					
R11A	AC	55,465	28,579	1,344,817	22,050
	PCC	225,000	712,999	146,070	1,064,023
	SL	18,065	16,755	16,585	16,865
R09A	AC	556,267	100,000	74,981	209,056
	PCC	225,000	1,000,000	1,539,875	138,686
	SL	9,227	8,927	9,292	9,292
R15A	AC	225,112	811,063	2,672,129	1,858,855
	PCC	101,095	49,312	14,359	22,293
	SL	17,488	16,736	18,143	18,119
A511					
A05B	AC	746,746	445,198	746,746	332,503
	PCC	10,000,000	10,587,054	10,000,000	11,770,956
	CL	13,817	19,302	13,817	19,162

Section	Material	WESDEF 'expert'	WESDEF inside limits	WESDEF outside limits	METHA
A15B	AC	424,161	424,161	338,678	479,069
	PCC	3,442,336	3,442,336	4,276,992	3,153,024
	CL	11,696	11,696	10,913	11,696
T09B	AC	2,414,290	884,141	2,414,290	1,466,019
	PCC	1,319,288	3,000,784	1,319,288	1,967,912
	CL	13,373	13,500	13,373	13,500

Overall, the majority of the Metha results were reasonable when comparing the backcalculated results to the modulus ranges presented previously. Also, subgrade moduli (AC, PCC, and composite) backcalculated using WESDEF were similar to those backcalculated using the Metha approach. For the base layers, the Metha approach resulted in slightly higher base moduli for the AC pavements and lower moduli for the PCC base layers. In general, no clear trend could be determined for the AC surface moduli calculated using the Metha approach, as both higher and lower moduli were backcalculated compared with WESDEF results. For the PCC surface moduli, the results tended to be lower than those backcalculated using WESDEF. For the composite pavements, no clear trend could be determined for the surface and base moduli compared to WESDEF results. Overall, the Metha approach may be a suitable check for comparing the subgrade moduli for an inexperienced user regardless of pavement type.

5.3.3 Benchmarking approach

The benchmarking approach to assigning pavement layer ratings presented by Horak and Emory (2009) in Chapter 3 was applied to the AC pavement sections. No benchmarking values exist for PCC or composite sections. The representative deflection basins (from WESDEF analyses) were used to compute the benchmarking parameters of D_0, BLI, MLI, and LLI, as described in Chapter 3.

Following the second approach presented in Chapter 3, benchmarking values were derived for an HWD contact stress of 442 psi for a flexible pavement on granular base and are presented in Table 30. Prior to computing the benchmarking parameters, the deflections were normalized to a load of 50,000 lb. Table 31 presents the benchmarking results for the AC sections.

Table 30. Proposed benchmark ranges for 442 psi HWD (50,000-lb load) contact stress on a granular base airport pavement (using second approach).

Structural Condition Rating	Deflection Basin Parameters			
	D_0 (mils)	BLI (mils)	MLI (mils)	LLI (mils)
Sound	<110	<43	<22	<11
Warning	110-162	43-86	22-43	11-22
Severe	>162	>86	>43	>22

Table 31. Benchmarking results for AC sections.

Section	Location	D_0	BLI (mils)	MLI (mils)	LLI (mils)	Benchmarking Structural Rating[a]
T23C	Pope Field	54	16	14	8	Green/Green/Green/Green
A21B	Pope Field	58	17	15	9	Green/Green/Green/Green
R09C2	Pope Field	34	7	7	5	Green/Green/Green/Green
R10A	Campbell AAF	100	46	33	11	Green/Yellow/Yellow/Green
T16C	Campbell AAF	86	36	24	11	Green/Green/Yellow/Green
T07C	Campbell AAF	51	23	12	6	Green/Green/Green/Green
T20B	Biggs AAF	62	25	18	10	Green/Green/Green/Green
R11A	Wheeler Sack AAF	38	7	8	6	Green/Green/Green/Green
T02A	Wheeler Sack AAF	43	12	11	6	Green/Green/Green/Green
T21B	Wheeler Sack AAF	52	15	13	8	Green/Green/Green/Green

[a] See Table 30 for color codes.

Comparing the BLI, MLI, and LLI values to backcalculated moduli for AC sections presented in Table 17, the Yellow benchmarking "Warning" for the BLI and MLI for R10A indicate that the moduli for the base and subbase may be weaker than anticipated for these type materials. R10A did not have a subbase, but the backcalculated moduli of 14,405 psi is low for a crushed stone base course material. The Warning MLI for T16C indicates that the subbase material is weak. For a 15-in. dense-graded aggregate, the backcalculated subbase moduli of 16,333 is low. Using this method identified weak sublayers based on deflection measurements alone. The weak sublayers corresponded with low backcalculated moduli. Based on these preliminary results, this method can be applied as a check for backcalculated moduli.

This method may also be useful for identifying weak areas in a pavement feature if applied to every station where HWD data are collected. The

HWD results for R10A at Campbell AAF were selected as an example. This section had 26 stations tested. Using the deflection basins for the highest load level (usually the third drop for current airfield practices), the benchmarking parameters were plotted in Figure 20 for D_0, Figure 21 for BLI, Figure 22 for MLI, and Figure 23 for LLI. Overall, the surface parameters indicate strong pavement, but the base (BLI) and subgrade (LLI) indicate weaker sublayers than expected for an AC pavement under a 50,000-lb load. All four plots indicate that there is a weak area at Station 16 and that the pavement is stronger in the last few stations.

WESDEF identified Station 13 as the representative basin (having the least error between measured and computed moduli). The plots were reviewed to determine whether this station is representative of the stations tested. This station had a D_O measurement in the Sound category, which is similar to most of the other stations. Station 13's BLI was in the Warning category, and overall, it is representative of all the stations collected. Station 13's LLI was in the Sound category, but this was not representative of the overall structure. These plots indicate that sta 13 was not representative of the overall section response to a 50,000-lb load.

Figure 20. D_O parameter plot for Campbell AAF Section R10A.

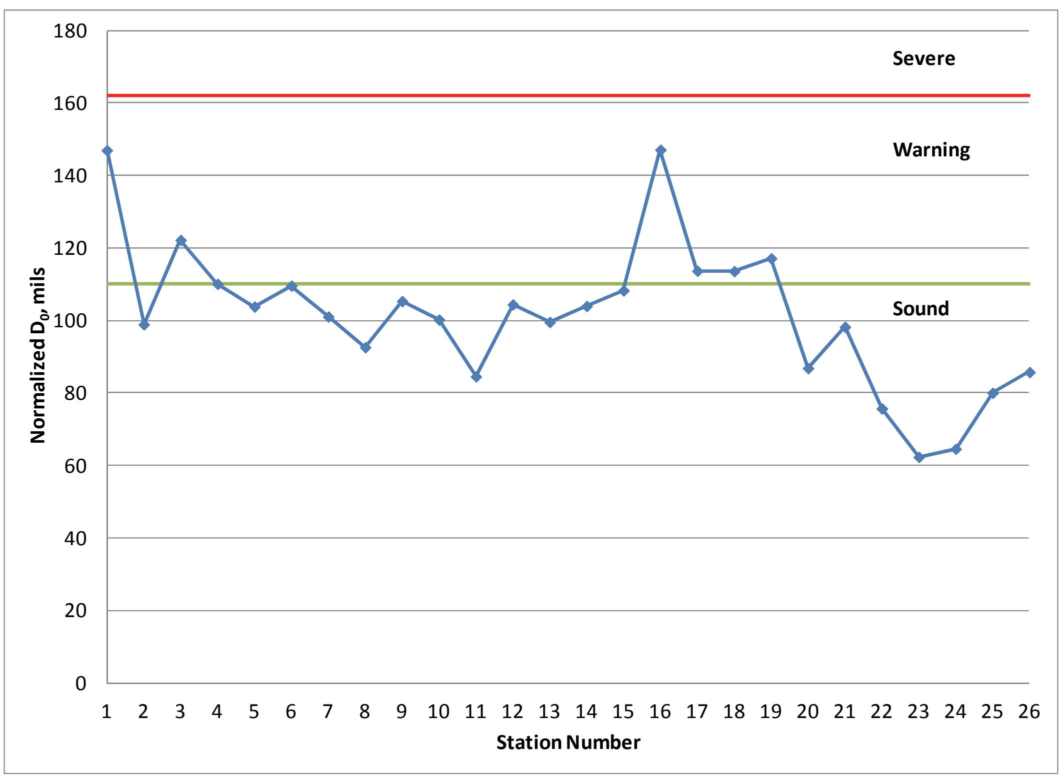


Figure 21. BLI parameter plot for Campbell AAF Section R10A.

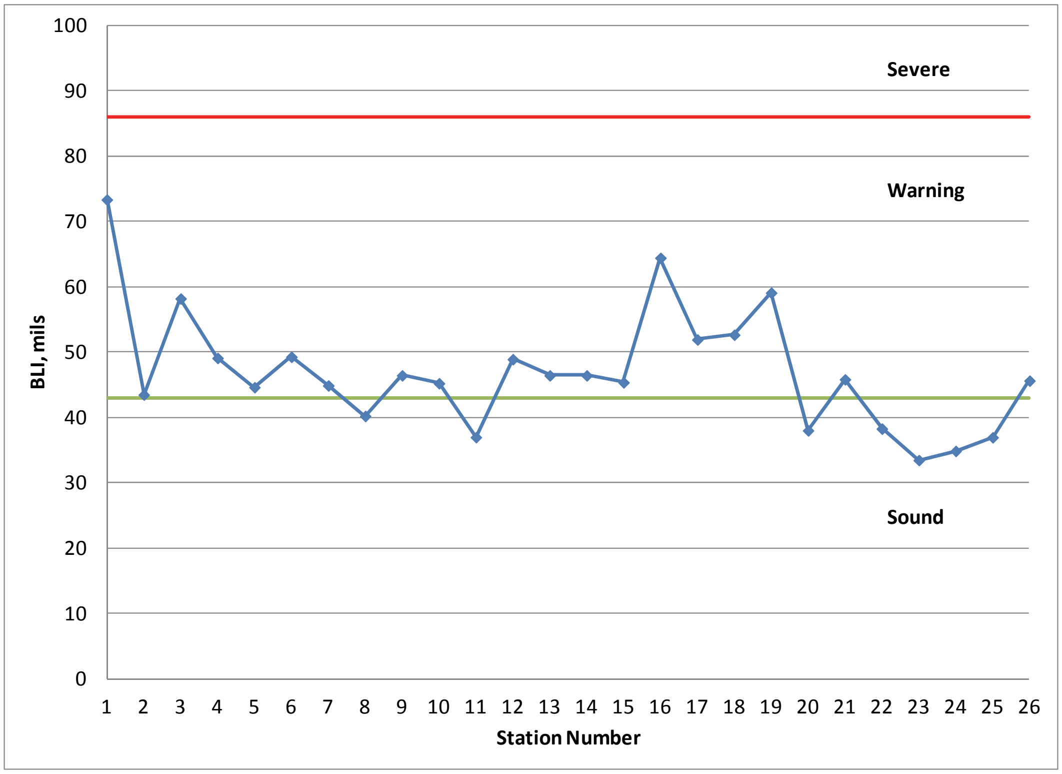


Figure 22. MLI parameter plot for Campbell AAF Section R10A.

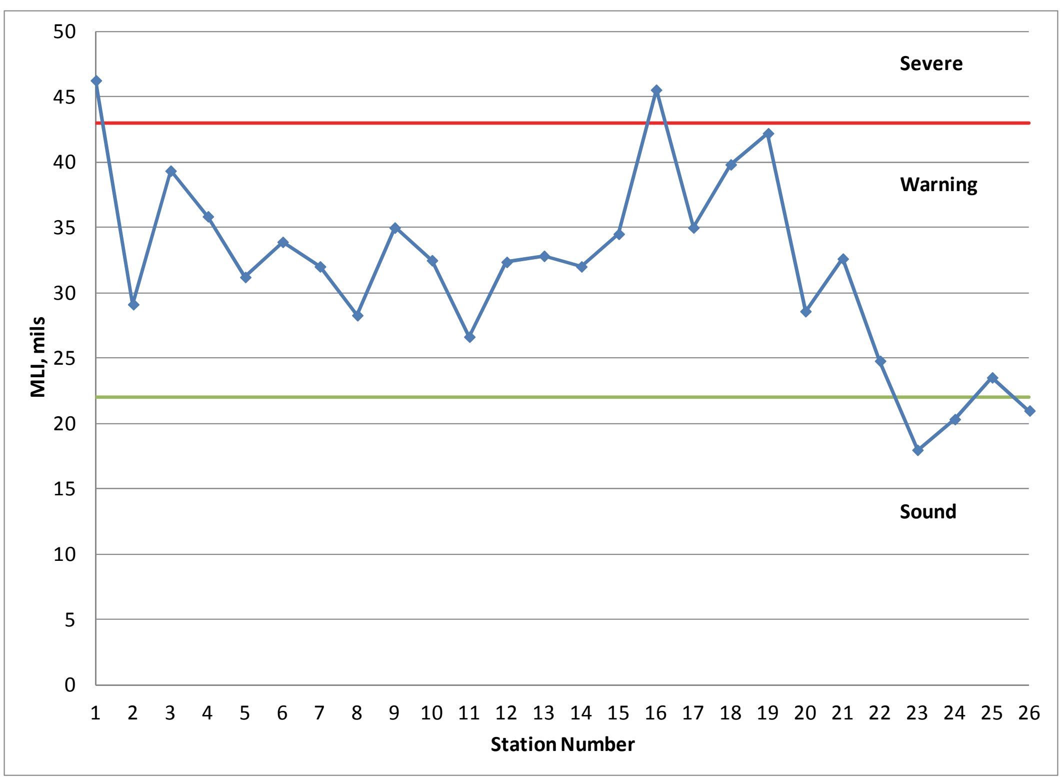
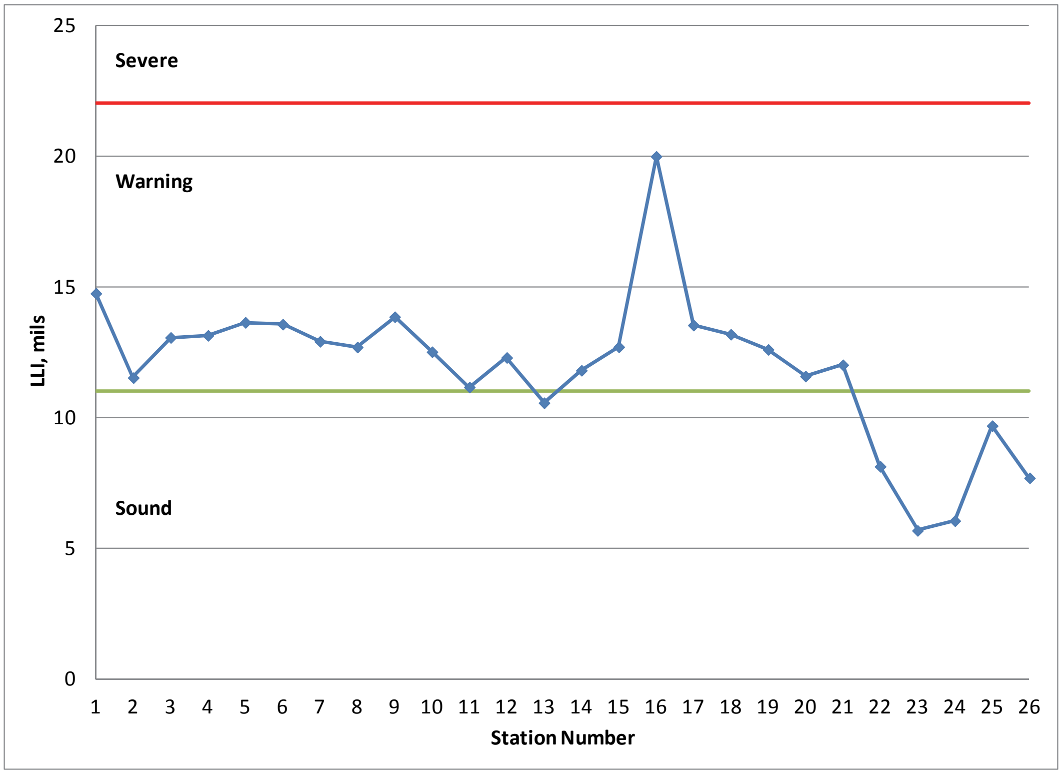


Figure 23. LLI parameter plot for Campbell AAF Section R10A.



An attempt was made to determine whether benchmarking values for composite pavements could be based on AC on cementitious base values presented in Chapter 3. Following the same approach for flexible pavements on granular base, benchmarking values were derived for an HWD contact stress of 442 psi, presented in Table 32. As with the AC over base sections, prior to computing the benchmarking parameters, the deflections were normalized to a load of 50,000 lb. Table 33 presents the benchmarking results for composite sections.

Table 32. Proposed benchmark ranges for 442 psi HWD (50,000-lb load) contact stress on a granular base airport pavement (using second approach).

Structural Condition Rating	Deflection Basin Parameters			
	D_0 (mils)	BLI (mils)	MLI (mils)	LLI (mils)
Sound	<43	<22	<11	<11
Warning	43-86	22-65	11-22	11-16
Severe	>86	>65	>22	>16

Table 33. Benchmarking results for composite sections.

Section	Location	D_0	BLI (mils)	MLI (mils)	LLI (mils)	Benchmarking Structural Rating
A14B	Pope Field	34	6	5	5	Green/Green/Green/Green
A16B1	Pope Field	32	7	6	5	Green/Green/Green/Green
A16B2	Pope Field	56	13	14	9	Yellow/Green/Yellow/Green
R01A	Campbell AAF	12	5	1	0	Green/Green/Green/Green
R11A	Phillips AAF	104	54	15	11	Red/Yellow/Yellow/Yellow
R09A	Phillips AAF	92	27	15	13	Red/Yellow/Yellow/Yellow
R15A	Phillips AAF	95	36	26	14	Red/Yellow/Red/Yellow
A05B	A511	17	2	1	1	Green/Green/Green/Green
A15B	A511	38	5	5	5	Green/Green/Green/Green
T09B	A511	32	4	4	4	Green/Green/Green/Green

Comparing the BLI, MLI, and LLI values to backcalculated moduli for composite sections presented in Table 17, the Yellow benchmarking Warning for the D_0 and MLI for A16B2 indicate that the moduli for the surface and subbase may be weaker than anticipated for these types of materials. The backcalculated moduli for the PCC base slabs was low (211,083 psi) compared to those of the PCC slabs, and the D_0 may indicate this. For backcalculation, the subbase was combined with the subgrade because the subbase was closer in strength to a subgrade material, so these results agree with the benchmarking results. R11A had a Severe indicator for the surface material, which corresponded to low values, for both the AC surface and PCC base slabs and also picked up in the Warning indicators for the base and subbase materials. As with A16B2, the subbase was combined with the subgrade, but the backcalculated moduli did not appear to be unreasonably low. Similar results were found for R09A and R15A, which correspond with low moduli for the surface, base, and subgrade. These results were able to identify weak layers for the composite pavements that compare well with the backcalculated moduli. Based on these preliminary results, this method could be applied as a check for backcalculated moduli.

These results indicate that the benchmarking method can be useful in selecting a representative station for analysis and for determining whether backcalculated moduli calculated for that station are reasonable. Unfortunately, benchmarking parameters are available only for AC pavements. The parameters derived for AC over cementitious base were applied to composite pavements. These appeared to adequately identify weak pavement layers. Additional research is required to determine parameters for PCC.

6 Structural Evaluation Using Backcalculated Moduli

6.1 Procedure

Because the purpose of backcalculating moduli is to determine the remaining life of a pavement, the impact of using modulus results from each backcalculation technique and program was investigated using the evaluation mode in the PCASE software. The method of evaluation followed the USAF's method. The USAF's method does not always use the actual backcalculated moduli for surface layers during the structural evaluation, and if they are excessively high, then the user will cap the moduli or use the modulus based on the temperature of the pavement at the time of test for analysis. The backcalculated moduli for the remaining sublayers (base, subbase, and subgrade) are, however, used for the analysis. The following procedures are used for capping rigid and flexible pavement layers for structural analyses:

Rigid pavements

- For rigid pavements with a backcalculated PCC modulus greater than 5,000,000 psi, the PCC modulus is capped at 5,000,000 psi for analysis (Army uses 4,000,000 psi).
- If the backcalculated modulus is under 5,000,000 psi, the backcalculated PCC modulus is used.

Thick AC layers (greater than 3 in.)

- If the AC pavement layer is less than 4 years old and the backcalculated modulus value is less than 350,000 psi, then the backcalculated AC modulus is used; otherwise, the value is set at 350,000 psi.
- If the AC pavement layer is between 4 and 10 years old and the backcalculated modulus is less than 500,000 psi, then the backcalculated value is used; otherwise, the value is set at 500,000 psi.
- If the AC pavement layer is between 10 and 20 years old and the backcalculated modulus is less than 750,000 psi, then the backcalculated modulus is used; otherwise, the value is set at 750,000 psi.

- If the AC pavement layer is over 20 years old, and the backcalculated modulus is less than 1,000,000 psi, then the backcalculated modulus is used; otherwise, the value is set to 1,000,000 psi.
- If the PSPA measured modulus if available, it is used for analysis.
- Note: This procedure is not used by the Army for its evaluations. The Army uses a temperature/design modulus based on temperature at the time of test.

Thin AC layers (less than 3 in.)

- Use the temperature/design modulus.

Composite pavements (AC/PCC) based on draft guidance for evaluating composite pavements provided in UFC 3-260-03 (revised draft 2007)

- If the flexural strength of the PCC base layer is less than 400 psi or the modulus of subgrade reaction (k) for the foundation layers beneath the PCC is greater than 200 pci, then the pavement should be evaluated as both a rigid pavement and as a flexible pavement to determine which yields the higher allowable gross weight for the selected pass level. The one with the higher allowable gross weight is then selected.
- If the preceding conditions do not apply, then the pavement is evaluated as a rigid pavement. When evaluating the system as a rigid pavement, then the AC and PCC layers are converted to an equivalent PCC layer thickness using the equation presented in Chapter 2. The surface distresses of the pavement must be taken into account to complete these calculations, and the USAF uses a spreadsheet with guidance for best calculating the equivalent thickness (Personal Communication with Dick Smith, AFCEC 2014).

Additional composite pavement guidance is provided by USAF (Personal communication with George VanSteenburg, AFCEC August 2014):

- In some cases, the pavement structure is evaluated as AC over a high-quality stabilized base if the AC thickness is more than 3 in. and the backcalculated modulus for the PCC is low (less than 4,000,000 psi). This is based on the assumption that at some point, the rigid PCC base slabs will tend to act more like a high-quality base material than a PCC surface course. When this condition is reached, then the AC overlay

should be used as the surface layer with the PCC base layers modeled as a high-quality base or stabilized base material.
- If the AC thickness is thin (less than 3 in.), PCC modulus values are very low (less than 2,000,000 psi), and the backcalculated errors are high, the system should be analyzed again as an equivalent PCC thickness and evaluated using these backcalculated values for PCC analysis.

Because the process is not straightforward, additional composite pavement guidance from the Army is provided as follows (Personal communication with Andrew Harrison, ERDC July 2014):

- Backcalculate the moduli as a flexible pavement if the AC thickness is more than 3 in. with an AC surface, high-quality stabilized base for the PCC, and sublayers. Cap the base modulus to 1,000,000 psi for analysis and analyze as a flexible pavement.
- If the AC thickness is thin (less than 3 in.) and the backcalculated errors are high, the surface thickness may sometimes be ignored and the system analyzed with the PCC base slab thickness as the surface material (rigid pavement analysis). Alternatively, the modulus of the AC may be set based on temperature at the time of test and the system evaluated as a flexible pavement.

As a note, for the FAA, if the AC thickness is greater than one-half the total AC and PCC thickness, then the system is evaluated as a flexible pavement. There is continuing discussion within the DoD as to what thickness AC is required to set firm guidance on what to do with thin AC layers over PCC base slabs. Regardless of the method used, multiple trials are generally necessary to determine the remaining pavement life.

For comparison purposes, the structural analysis consisted of evaluating each pavement section for its ability to support a simplified traffic pattern (instead of the typical USAF 14 Group patterns) consisting of 50,000 passes of a C-17 aircraft loaded to 585,000 lb. Layer thicknesses, flexural strength, AC surface age, and the PCI for each pavement are presented in Table 34. While it is standard practice to reduce the allowable load for pavements with PCIs below 40, no load reductions were applied, as these computations were done for comparison purposes only.

Table 34. Layer properties required for structural evaluation.

Section	Layer	Material	Thickness, in.	PCC Flexural Strength, psi	AC age years	PCI
Pope Field						
R01A	PCC	PCC	12	749	-----	90
	Base	Sand	20	-----	-----	
	Natural Subgrade	SM	208	-----	-----	
A27B	PCC	PCC	15.5	705	-----	95
	HQ Stab Base	Macadam	3.25	-----	-----	
	Comp Subgrade	SW-SM	221.25	-----	-----	
T05A	PCC	PCC	15	728	-----	80
	Base	GW	8	-----	-----	
	Comp Subgrade	SP-SM	217	-----	-----	
T23C	Asphalt	AC	4.5	-----	11	74
	Base	GW-GM	24	-----	-----	
	Natural Subgrade	SW-SM	211.5	-----	-----	
A21B	Asphalt	AC	6.5	-----	25	36
	Base	GP-GM	6	-----	-----	
	Subbase	SC	22	-----	-----	
	Natural Subgrade	SC	205.5	-----	-----	
R09C2	Asphalt	AC	8.75	-----	2	90
	Base	GP-GM	5	-----	-----	
	Comp Subgrade	SM	226.25	-----	-----	
A14B	Asphalt	AC	4	-----	20	51
	HQ Stab Base	PCC	6	800	-----	
	Comp Subgrade	SM	230	-----	-----	
A16B1	Asphalt	AC	4.5	-----	22	39
	HQ Stab Base	PCC	5.25	800	-----	
	Comp Subgrade	SC	230.25	-----	-----	
A16B2	Asphalt	AC	4.5	-----	22	65
	HQ Stab Base	PCC	5.25	800	-----	
	Comp Subgrade	SC	230.25	-----	-----	
Campbell AAF						
A22B	PCC	PCC	6	700	-----	78
	Natural Subgrade	CL	234	-----	-----	
A14B	PCC	PCC	7	700	-----	81
	Natural Subgrade	CL	233	-----	-----	

Section	Layer	Material	Thickness, in.	PCC Flexural Strength, psi	AC age years	PCI
T02A	PCC	PCC	14	725		85
	Base	GW	17	-----	-----	
	Comp Subgrade	CL	209	-----	-----	
R10A	Asphalt	AC	5	-----	4	71
	Base	GW	10	-----	-----	
	Natural Subgrade	CL	225	-----	-----	
T16C	Asphalt	AC	5	-----	5	100
	Base	GW	5	-----	-----	
	Subbase	Dense-Graded Aggregate	15	-----	-----	
	Natural Subgrade	CL	215			
T07C	Asphalt	AC	6	-----	22	66
	Base	Water-Bound Macadam	9	-----	-----	
	Subbase	GW	17	-----	-----	
	Comp Subgrade	CL	208	-----	-----	
R01A	Asphalt	AC	11	-----	8	71
	HQ Stab Base	PCC	16	600	-----	
	Natural Subgrade	CL	213	-----	-----	
Biggs AAF						
A03B	PCC	PCC	17.5	528	-----	99
	Comp Subgrade	SM-SC	222.5	-----	-----	
A26B	PCC	PCC	11	592	-----	97
	Comp Subgrade	SM	229	-----	-----	
R03A	PCC	PCC	25	622	-----	67
	Comp Subgrade	SM-SC	215	-----	-----	
T16A	PCC	PCC	20	517	-----	92
	Comp Subgrade	SM-SC	220	-----	-----	
T20B	Asphalt	AC	4	-----	60	5
	Base	Clayey Sandy Gravel	10	-----	-----	
	Comp Subgrade	SM	226	-----	-----	
Wheeler Sack AAF						
R11A	Asphalt	AC	8	-----	2	100
	Base	Aggregate Base	8	-----	-----	
	Natural Subgrade	SP	224	-----	-----	

Section	Layer	Material	Thickness, in.	PCC Flexural Strength, psi	AC age years	PCI
T02A	Asphalt	AC	6	-----	22	76
	Base	Granular Base	10	-----	-----	
	Natural Subgrade	SP	224	-----	-----	
T21B	Asphalt	AC	6	-----	22	76
	Base	Granular Base	10	-----	-----	
	Natural Subgrade	SP	224	-----	-----	
Phillips AAF						
R11A	Asphalt	AC	3.5	-----	58	7
	Stab Base	PCC	6	600	-----	
	Comp Subgrade	SL	230.5	-----	-----	
R09A	Asphalt	AC	4	-----	58	18
	Stab Base	PCC	6	600	-----	
	Comp Subgrade	SL	230	-----	-----	
R15A	Asphalt	AC	3	-----	58	27
	Stab Base	PCC	6	600	-----	
	Comp Subgrade	SL	231	-----	-----	
A511						
A05B	Asphalt	AC	4	-----	3	70
	HQ Stab Base	PCC	8	700	-----	
	Natural Subgrade	CL	228	-----	-----	
A15B	Asphalt	AC	4	-----	18	41
	HQ Stab Base	PCC	8	600	-----	
	Natural Subgrade	CL	228	-----	-----	
T09B	Asphalt	AC	4	-----	7	42
	HQ Stab Base	PCC	8	600	-----	
	Natural Subgrade	CL	228	-----	-----	

For each section, multiple analyses were conducted in PCASE using the pavement layer properties provided in Table 34 and the backcalculated modulus values presented previously in Table 23. PCASE reported values include the aircraft classification number (ACN), the pavement classification number (PCN), the ACN/PCN ratio, and the computed allowable load. Overlays may also be computed; however, it is not USAF procedure to report overlays.

For clarity: the PCN is a representation of the allowable load for a specified number of repetitions over the life of a pavement, and the ACN is a representation of the load applied by an aircraft using the pavement. For evaluation purposes the ACN/PCN ratio is computed and shown in the tables. An aircraft operating at an ACN equal to or less than the PCN, or ACN/PCN ratio ≤ 1.0, would comply with load restrictions established based on a specified design life for the pavement facility (in this case 50,000 passes of the C-17). However, if the ACN is greater than the PCN, or ACN/PCN >1, the pavement design life is shortened due to overloading. Pavements can usually support some overload; nevertheless, there is a reduction in pavement life. If the operational ACN is greater than the pavement PCN and a decrease in pavement life is not acceptable, then structural improvement of the pavement is required to increase the pavement PCN up to or greater than the operational ACN.

In general, ACN/PCN ratios equal to or less than 1.1 have minimal impact on pavement life. If the ACN/PCN ratio is greater than 1.1 and less than or equal to 1.4, aircraft operations should be limited to 10 passes and the pavement inspected after each operation. Aircraft operations resulting in an ACN/PCN ratio greater than 1.4 should not be allowed except for emergencies. Refer to UFC 3-260-02 (2001) for additional details.

In this investigation, for both AC and PCC pavements, if the surface moduli were below the capped analysis value, then those values were used. If the surface moduli were above the capped values, then the analysis was conducted twice: (1) with the backcalculated surface values and (2) with the capped surface values. For the AC analyses, the backcalculated moduli were used in lieu of temperature-based moduli for the AC pavements following the USAF procedure.

For rigid pavements, the flexural strength of the material was used for analysis measured either through historic or recent core data or collected using the PSPA. The age of each flexible pavement was determined through review of construction history records for each airfield to show the effect of capping the surface modulus compared to using the backcalculated results.

Because the guidance for composite pavements is not firm, two different analysis methods were used. For composite pavements, the backcalculated moduli (from each program) were first used to evaluate the pavements as flexible pavements (using AC surface, high-quality stabilized base, and subgrade as the pavement model). Additional analyses were then conducted using the equivalent pavement thickness (PCC) and subgrade moduli computed using WESDEF to compare allowable loads from both flexible and rigid pavement results for the WESDEF moduli. The equivalent pavement thickness was computed using the USAF's equivalent thickness spreadsheet, assuming that there were few reflective cracks or just joint reflective cracks for computation purposes.

6.2 Results of structural analysis

6.2.1 PCC pavements

As shown in Table 35 for the PCC pavements, regardless of the software used, surface moduli above 5,000,000 psi (the capped value) resulted in higher ACN/PCN ratios because the pavement is considered more brittle, resulting in lower PCN values. When the surface modulus was capped (or less than 5,000,000 psi), then the results were primarily controlled by the computed subgrade moduli. This led to similar results for WESDEF and BAKFAA ACN/PCN ratios and allowable loads. This is not unexpected, as the subgrade moduli were similar for these programs. Additionally, when the surface moduli were capped, the ACN/PCN results for WESDEF expert and inexperienced user results were similar. This indicates that an inexperienced user would potentially obtain similar structural evaluation results as long as the moduli were limited to less than 5,000,000 psi for the surface. Additional analyses of more sections are required to confirm these preliminary conclusions. Overall, the ELMOD6 moduli resulted in higher allowable loads and lower ACN/PCN ratios than the other programs. This is due to ELMOD6's lower estimated base layer moduli and higher estimated subgrade moduli compared to the other programs.

Table 35. Structural evaluation results for PCC sections.

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
Pope Field					
R01A	WESDEF 'expert'	50/R/B/W/T	47/R/B/W/T	1.1	552.50
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	50/R/B/W/T	45/R/B/W/T	1.1	535.40
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	50/R/B/W/T	47/R/B/W/T	1.1	552.50
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'expert seed'	50/R/B/W/T	45/R/B/W/T	1.1	532.10
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	50/R/B/W/T	45/R/B/W/T	1.1	532.70
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	50/R/B/W/T	50/R/B/W/T	1.0	591.90
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 ‘representative basin’	50/R/B/W/T	55/R/B/W/T	0.9	648.60
	ELMOD6 ‘representative basin,’ capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 ‘LET’	50/R/B/W/T	59/R/B/W/T	0.8	691.90
	ELMOD6 ‘LET,’ capped	--[a]	--[a]	--[a]	--[a]
	METHA	50/R/B/W/T	43/R/B/W/T	1.2	511.60
	METHA, capped	--[a]	--[a]	--[a]	--[a]
A27B	WESDEF 'expert'	54/R/C/W/T	48/R/C/W/T	1.1	529.20
	WESDEF 'expert,' capped	54/R/C/W/T	58/R/C/W/T	0.9	620.50
	WESDEF inside limits	54/R/C/W/T	50/R/C/W/T	1.1	551.30
	WESDEF inside limits, capped	54/R/C/W/T	63/R/C/W/T	0.9	674.60
	WESDEF outside limits	54/R/C/W/T	48/R/C/W/T	1.1	529.20
	WESDEF outside limits, capped	54/R/C/W/T	58/R/C/W/T	0.9	620.50
	BAKFAA 'expert seed'	54/R/C/W/T	44/R/C/W/T	1.2	487.50
	BAKFAA 'expert seed,' capped	54/R/C/W/T	51/R/C/W/T	1.1	559.70
	BAKFAA 'typical seed'	54/R/C/W/T	44/R/C/W/T	1.2	491.40
	BAKFAA 'typical seed,' capped	54/R/C/W/T	52/R/C/W/T	1.0	562.80
	ELMOD6 mean	50/R/B/W/T	48/R/B/W/T	1.0	570.80
	ELMOD6 mean, capped	50/R/B/W/T	51/R/B/W/T	1.0	603.20
	ELMOD6 ‘representative basin’	50/R/B/W/T	50/R/B/W/T	1.0	587.50
	ELMOD6 ‘representative basin,’ capped	50/R/B/W/T	51/R/B/W/T	1.0	600.10
	ELMOD6 ‘LET’	54/R/C/W/T	55/R/C/W/T	1.0	595.00
	ELMOD6 ‘LET,’ capped	54/R/C/W/T	64/R/C/W/T	0.8	682.00
	METHA	54/R/C/W/T	45/R/C/W/T	1.2	500.40
	METHA, capped	54/R/C/W/T	60/R/C/W/T	0.9	647.50
T05A	WESDEF 'expert'	50/R/B/W/T	85/R/B/W/T	0.6	1,008.60
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	50/R/B/W/T	51/R/B/W/T	1.0	605.00
	WESDEF inside limits, capped	50/R/B/W/T	55/R/B/W/T	0.9	652.80
	WESDEF outside limits	50/R/B/W/T	85/R/B/W/T	0.6	1,008.60
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'expert seed'	50/R/B/W/T	50/R/B/W/T	1.0	584.60
	BAKFAA 'expert seed,' capped	50/R/B/W/T	53/R/B/W/T	0.9	621.90
	BAKFAA 'typical seed'	50/R/B/W/T	49/R/B/W/T	1.0	575.90
	BAKFAA 'typical seed,' capped	50/R/B/W/T	52/R/B/W/T	1.0	615.40
	ELMOD6 mean	50/R/B/W/T	58/R/B/W/T	0.9	679.50
	ELMOD6 mean, capped	50/R/B/W/T	58/R/B/W/T	0.9	682.70
	ELMOD6 'representative basin'	50/R/B/W/T	57/R/B/W/T	0.9	676.30
	ELMOD6 'representative basin,' capped	50/R/B/W/T	57/R/B/W/T	0.9	678.10
	ELMOD6 'LET'	50/R/B/W/T	47/R/B/W/T	1.1	549.10
	ELMOD6 'LET,' capped	50/R/B/W/T	58/R/B/W/T	0.9	688.80
	METHA	50/R/B/W/T	47/R/B/W/T	1.1	549.50
	METHA, capped	50/R/B/W/T	53/R/B/W/T	0.9	621.30
Campbell AAF					
A22B	WESDEF 'expert'	54/R/C/W/T	10/R/C/W/T	5.4	167.80
	WESDEF 'expert,' capped	54/R/C/W/T	10/R/C/W/T	5.4	172.80
	WESDEF inside limits	54/R/C/W/T	10/R/C/W/T	5.4	167.90
	WESDEF inside limits, capped	54/R/C/W/T	10/R/C/W/T	5.4	172.80
	WESDEF outside limits	54/R/C/W/T	10/R/C/W/T	5.4	167.90
	WESDEF outside limits, capped	54/R/C/W/T	10/R/C/W/T	5.4	172.80
	BAKFAA 'expert seed'	54/R/C/W/T	10/R/C/W/T	5.4	167.50
	BAKFAA 'expert seed,' capped	54/R/C/W/T	10/R/C/W/T	5.4	172.00
	BAKFAA 'typical seed'	54/R/C/W/T	10/R/C/W/T	5.4	167.00
	BAKFAA 'typical seed,' capped	54/R/C/W/T	10/R/C/W/T	5.4	167.50
	ELMOD6 mean	66/R/D/W/T	5/R/D/W/T	13.2	150.10
	ELMOD6 mean, capped	66/R/D/W/T	5/R/D/W/T	13.2	150.10
	ELMOD6 'representative basin'	66/R/D/W/T	3/R/D/W/T	22.0	137.10
	ELMOD6 'representative basin,' capped	66/R/D/W/T	4/R/D/W/T	16.5	145.80
	ELMOD6 'LET'	54/R/C/W/T	16/R/C/W/T	3.4	223.50
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	54/R/C/W/T	10/R/C/W/T	5.4	168.40
	METHA, capped	54/R/C/W/T	10/R/C/W/T	5.4	172.80
A14B	WESDEF 'expert'	54/R/C/W/T	16/R/C/W/T	3.4	228.60
	WESDEF 'expert,' capped	54/R/C/W/T	17/R/C/W/T	3.2	238.90
	WESDEF inside limits	54/R/C/W/T	16/R/C/W/T	3.4	228.70
	WESDEF inside limits, capped	54/R/C/W/T	17/R/C/W/T	3.2	238.90
	WESDEF outside limits	54/R/C/W/T	16/R/C/W/T	3.4	228.60

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	WESDEF outside limits, capped	54/R/C/W/T	17/R/C/W/T	3.2	238.90
	BAKFAA 'expert seed'	54/R/C/W/T	16/R/C/W/T	3.4	229.10
	BAKFAA 'expert seed,' capped	54/R/C/W/T	17/R/C/W/T	3.2	237.50
	BAKFAA 'typical seed'	54/R/C/W/T	16/R/C/W/T	3.4	229.10
	BAKFAA 'typical seed,' capped	54/R/C/W/T	17/R/C/W/T	3.2	237.50
	ELMOD6 mean	54/R/C/W/T	12/R/C/W/T	4.5	190.00
	ELMOD6 mean, capped	54/R/C/W/T	13/R/C/W/T	4.2	198.90
	ELMOD6 ‘representative basin’	54/R/C/W/T	11/R/C/W/T	4.9	182.00
	ELMOD6 ‘representative basin,’ capped	54/R/C/W/T	13/R/C/W/T	4.2	197.40
	ELMOD ‘LET’	54/R/C/W/T	23/R/C/W/T	2.3	295.30
	ELMOD6 ‘LET,’ capped	--[a]	--[a]	--[a]	--[a]
	METHA	54/R/C/W/T	17/R/C/W/T	3.2	235.40
	METHA, capped	54/R/C/W/T	17/R/C/W/T	3.2	238.90
T02A	WESDEF 'expert'	50/R/B/W/T	40/R/B/W/T	1.3	469.70
	WESDEF 'expert,' capped	50/R/B/W/T	45/R/B/W/T	1.1	533.90
	WESDEF inside limits	50/R/B/W/T	40/R/B/W/T	1.3	469.70
	WESDEF inside limits, capped	50/R/B/W/T	45/R/B/W/T	1.1	533.90
	WESDEF outside limits	50/R/B/W/T	40/R/B/W/T	1.3	469.70
	WESDEF outside limits, capped	50/R/B/W/T	45/R/B/W/T	1.1	533.90
	BAKFAA 'expert seed'	50/R/B/W/T	40/R/B/W/T	1.3	469.90
	BAKFAA 'expert seed,' capped	50/R/B/W/T	44/R/B/W/T	1.1	522.00
	BAKFAA 'typical seed'	50/R/B/W/T	41/R/B/W/T	1.2	477.10
	BAKFAA 'typical seed,' capped	50/R/B/W/T	45/R/B/W/T	1.1	527.90
	ELMOD6 mean	50/R/B/W/T	37/R/B/W/T	1.4	438.50
	ELMOD6 mean, capped	50/R/B/W/T	40/R/B/W/T	1.3	472.60
	ELMOD6 ‘representative basin’	50/R/B/W/T	37/R/B/W/T	1.4	440.60
	ELMOD6 ‘representative basin,’ capped	50/R/B/W/T	41/R/B/W/T	1.2	479.30
	ELMOD6 ‘LET’	50/R/B/W/T	42/R/B/W/T	1.2	496.50
	ELMOD ‘LET,’ capped	50/R/B/W/T	55/R/B/W/T	0.9	644.30
	METHA	50/R/B/W/T	41/R/B/W/T	1.2	482.60
	METHA, capped	50/R/B/W/T	46/R/B/W/T	1.1	542.00
Biggs AAF					
A03B	WESDEF 'expert'	54/R/C/W/T	42/R/C/W/T	1.3	472.60
	WESDEF 'expert,' capped	54/R/C/W/T	51/R/C/W/T	1.1	558.40
	WESDEF inside limits	54/R/C/W/T	26/R/C/W/T	1.2	512.70
	WESDEF inside limits, capped	54/R/C/W/T	50/R/C/W/T	1.1	546.30

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	WESDEF outside limits	54/R/C/W/T	42/R/C/W/T	1.3	470.10
	WESDEF outside limits, capped	54/R/C/W/T	51/R/C/W/T	1.1	556.60
	BAKFAA 'expert seed'	54/R/C/W/T	42/R/C/W/T	1.3	475.30
	BAKFAA 'expert seed,' capped	54/R/C/W/T	51/R/C/W/T	1.1	556.60
	BAKFAA 'typical seed'	54/R/C/W/T	42/R/C/W/T	1.3	475.30
	BAKFAA 'typical seed,' capped	54/R/C/W/T	51/R/C/W/T	1.1	556.70
	ELMOD6 mean	50/R/B/W/T	61/R/B/W/T	0.8	720.70
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 ‘representative basin’	50/R/B/W/T	58/R/B/W/T	0.9	685.70
	ELMOD6 ‘representative basin,’ capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 ‘LET’	50/R/B/W/T	37/R/B/W/T	1.4	433.00
	ELMOD6 ‘LET,’ capped	50/R/B/W/T	52/R/B/W/T	1.0	611.40
	METHA	50/R/B/W/T	49/R/B/W/T	1.0	579.90
	METHA, capped	50/R/B/W/T	51/R/B/W/T	1.0	600.50
A26B	WESDEF 'expert'	50/R/B/W/T	30/R/B/W/T	1.7	356.30
	WESDEF 'expert,' capped	50/R/B/W/T	32/R/B/W/T	1.6	379.20
	WESDEF inside limits	50/R/B/W/T	30/R/B/W/T	1.7	356.30
	WESDEF inside limits, capped	50/R/B/W/T	32/R/B/W/T	1.6	379.30
	WESDEF outside limits	50/R/B/W/T	30/R/B/W/T	1.7	356.30
	WESDEF outside limits, capped	50/R/B/W/T	32/R/B/W/T	1.6	379.30
	BAKFAA 'expert seed'	50/R/B/W/T	31/R/B/W/T	1.6	363.10
	BAKFAA 'expert seed,' capped	50/R/B/W/T	32/R/B/W/T	1.6	379.30
	BAKFAA 'typical seed'	50/R/B/W/T	31/R/B/W/T	1.6	363.20
	BAKFAA 'typical seed,' capped	50/R/B/W/T	32/R/B/W/T	1.6	379.30
	ELMOD6 mean	50/R/B/W/T	38/R/B/W/T	1.3	444.00
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 ‘representative basin’	50/R/B/W/T	40/R/B/W/T	1.3	471.30
	ELMOD6 ‘representative basin,’ capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 ‘LET’	50/R/B/W/T	34/R/B/W/T	1.5	395.30
	ELMOD6 ‘LET,’ capped	50/R/B/W/T	35/R/B/W/T	1.4	406.20
	METHA	50/R/B/W/T	30/R/B/W/T	1.7	357.80
	METHA, capped	50/R/B/W/T	32/R/B/W/T	1.6	377.00
R03A	WESDEF 'expert'	54/R/C/W/T	75/R/C/W/T	0.7	786.40
	WESDEF 'expert,' capped	54/R/C/W/T	91/R/C/W/T	0.6	937.60
	WESDEF inside limits	50/R/B/W/T	85/R/B/W/T	0.6	1,011.00
	WESDEF inside limits, capped	50/R/B/W/T	94/R/B/W/T	0.5	1,106.00

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	WESDEF outside limits	54/R/C/W/T	79/R/C/W/T	0.7	826.20
	WESDEF outside limits, capped	54/R/C/W/T	92/R/C/W/T	0.6	948.20
	BAKFAA 'expert seed'	54/R/C/W/T	74/R/C/W/T	0.7	770.90
	BAKFAA 'expert seed,' capped	54/R/C/W/T	90/R/C/W/T	0.6	926.30
	BAKFAA 'typical seed'	54/R/C/W/T	74/R/C/W/T	0.7	771.60
	BAKFAA 'typical seed,' capped	54/R/C/W/T	90/R/C/W/T	0.6	926.70
	ELMOD6 mean	50/R/B/W/T	104/R/B/W/T	0.5	1,231.90
	ELMOD6 mean, capped	50/R/B/W/T	106/R/B/W/T	0.5	1,253.20
	ELMOD6 'representative basin'	50/R/B/W/T	99/R/B/W/T	0.5	1,165.50
	ELMOD6 'representative basin,' capped	50/R/B/W/T	101/R/B/W/T	0.5	1,199.60
	ELMOD6 'LET'	50/R/B/W/T	64/R/B/W/T	0.8	758.70
	ELMOD6 'LET,' capped	50/R/B/W/T	101/R/B/W/T	0.5	1,197.10
	METHA	54/R/C/W/T	76/R/C/W/T	0.7	798.40
	METHA, capped	54/R/C/W/T	92/R/C/W/T	0.6	948.20
T16A	WESDEF 'expert'	54/R/C/W/T	43/R/C/W/T	1.3	481.50
	WESDEF 'expert,' capped	54/R/C/W/T	53/R/C/W/T	1.0	576.60
	WESDEF inside limits	54/R/C/W/T	46/R/C/W/T	1.2	514.00
	WESDEF inside limits, capped	54/R/C/W/T	55/R/C/W/T	1.0	600.30
	WESDEF outside limits	54/R/C/W/T	43/R/C/W/T	1.3	480.80
	WESDEF outside limits, capped	54/R/C/W/T	53/R/C/W/T	1.0	576.60
	BAKFAA 'expert seed'	54/R/C/W/T	43/R/C/W/T	1.3	486.30
	BAKFAA 'expert seed,' capped	54/R/C/W/T	53/R/C/W/T	1.0	576.90
	BAKFAA 'typical seed'	54/R/C/W/T	43/R/C/W/T	1.3	486.20
	BAKFAA 'typical seed,' capped	54/R/C/W/T	53/R/C/W/T	1.0	576.00
	ELMOD6 mean	50/R/B/W/T	64/R/B/W/T	0.8	758.90
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	50/R/B/W/T	60/R/B/W/T	0.8	704.80
	ELMOD6 'representative basin,' capped	50/R/B/W/T	63/R/B/W/T	0.8	742.00
	ELMOD6 'LET'	50/R/B/W/T	46/R/B/W/T	1.1	544.40
	ELMOD6 'LET,' capped	50/R/B/W/T	57/R/B/W/T	0.9	672.50
	METHA	54/R/C/W/T	44/R/C/W/T	1.2	496.50
	METHA, capped	54/R/C/W/T	53/R/C/W/T	1.0	579.90

[a] Surface modulus below 5,000,000 psi; therefore, the backcalculated modulus was used and not capped.

6.2.2 AC pavements

As shown in Table 36, for the AC pavements, generally, the ELMOD6 backcalculated moduli resulted in ACN/PCN values that were lower than those obtained using WESDEF or BAKFAA results, resulting in higher allowable loads. This is not unexpected, as the sublayer moduli were similar for WESDEF and BAKFAA, but ELMOD6's subgrade moduli were higher than the other programs'. For three of the sections (Pope T23C and R09C2 and Wheeler Sack R11A), when the surface moduli were capped based on the age of the AC layer, then the capped results were similar for PCASE and BAKFAA and in some cases for ELMOD6 representative basin results. Additionally, the ACN/PCN results for WESDEF expert and inexperienced user results were similar. This indicates that an inexperienced user would potentially obtain similar structural evaluation results using PCASE without manipulating the seed moduli. Additional analyses of more sections are required to confirm these preliminary conclusions.

Table 36. Structural evaluation results for AC sections.

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
Pope Field					
T23C	WESDEF 'expert'	45/F/B/W/T	41/F/B/W/T	1.10	544.80
	WESDEF 'expert,' capped	45/F/B/W/T	48/F/B/W/T	0.94	626.10
	WESDEF inside limits	45/F/B/W/T	41/F/B/W/T	1.10	544.60
	WESDEF inside limits, capped	45/F/B/W/T	48/F/B/W/T	0.94	625.80
	WESDEF outside limits	45/F/B/W/T	41/F/B/W/T	1.10	544.80
	WESDEF outside limits, capped	45/F/B/W/T	48/F/B/W/T	0.94	626.10
	BAKFAA 'expert seed'	45/F/B/W/T	43/F/B/W/T	1.05	566.80
	BAKFAA 'expert seed,' capped	45/F/B/W/T	50/F/B/W/T	0.90	647.00
	BAKFAA 'typical seed'	45/F/B/W/T	43/F/B/W/T	1.05	566.70
	BAKFAA 'typical seed,' capped	45/F/B/W/T	50/F/B/W/T	0.90	646.90
	ELMOD6 mean	40/F/A/W/T	39/F/A/W/T	1.03	572.80
	ELMOD6 mean, capped	40/F/A/W/T	43/F/A/W/T	0.93	617.70
	ELMOD6 'representative basin'	45/F/B/W/T	46/F/B/W/T	0.98	596.60
	ELMOD6 'representative basin,' capped	45/F/B/W/T	50/F/B/W/T	0.90	649.40
	ELMOD6 'LET'	45/F/B/W/T	66/F/B/W/T	0.68	820.60
	ELMOD6 'LET,' capped	45/F/B/W/T	75/F/B/W/T	0.60	914.80
	METHA	45/F/B/W/T	71/F/B/W/T	0.63	870.30
	METHA, capped	45/F/B/W/T	76/F/B/W/T	0.59	929.10

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
A21B	WESDEF 'expert'	45/F/B/W/T	36/F/B/W/T	1.25	486.90
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	45/F/B/W/T	36/F/B/W/T	1.25	486.90
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	45/F/B/W/T	36/F/B/W/T	1.25	494.80
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	45/F/B/W/T	35/F/B/W/T	1.29	481.80
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	45/F/B/W/T	35/F/B/W/T	1.29	481.80
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	53/F/C/W/T	56/F/C/W/T	0.95	609.90
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	53/F/C/W/T	58/F/C/W/T	0.91	633.20
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	38/F/A/W/T	1.05	557.40
	ELMOD6 'LET,' capped	40/F/A/W/T	29/F/A/W/T	1.38	447.50
	METHA	45/F/B/W/T	36/F/B/W/T	1.25	494.80
	METHA, capped	--[a]	--[a]	--[a]	--[a]
R09C2	WESDEF 'expert'	40/F/A/W/T	59/F/A/W/T	0.68	813.50
	WESDEF 'expert,' capped	40/F/A/W/T	46/F/A/W/T	0.87	659.90
	WESDEF inside limits	40/F/A/W/T	53/F/A/W/T	0.75	740.20
	WESDEF inside limits, capped	40/F/A/W/T	48/F/A/W/T	0.83	680.50
	WESDEF outside limits	40/F/A/W/T	73/F/A/W/T	0.55	991.90
	WESDEF outside limits, capped	40/F/A/W/T	55/F/A/W/T	0.73	768.40
	BAKFAA 'expert seed'	40/F/A/W/T	46/F/A/W/T	0.87	658.90
	BAKFAA 'expert seed,' capped	40/F/A/W/T	40/F/A/W/T	1.00	586.80
	BAKFAA 'typical seed'	40/F/A/W/T	44/F/A/W/T	0.91	632.90
	BAKFAA 'typical seed,' capped	40/F/A/W/T	39/F/A/W/T	1.03	574.80
	ELMOD6 mean	40/F/A/W/T	73/F/A/W/T	0.55	996.80
	ELMOD6 mean, capped	40/F/A/W/T	59/F/A/W/T	0.68	818.90
	ELMOD6 'representative basin'	45/F/B/W/T	67/F/B/W/T	0.67	830.60
	ELMOD6 'representative basin,' capped	45/F/B/W/T	55/F/B/W/T	0.82	698.20
	ELMOD6 'LET'	40/F/A/W/T	53/F/A/W/T	0.75	750.20
	ELMOD6 'LET,' capped	40/F/A/W/T	53/F/A/W/T	0.75	743.10

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	METHA	40/F/A/W/T	36/F/A/W/T	1.11	532.50
	METHA, capped	40/F/A/W/T	37/F/A/W/T	1.08	539.30
Campbell AAF					
R10A	WESDEF 'expert'	40/F/A/W/T	17/F/A/W/T	2.35	300.20
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	40/F/A/W/T	15/F/A/W/T	2.67	269.20
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	40/F/A/W/T	15/F/A/W/T	2.67	269.20
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	40/F/A/W/T	16/F/A/W/T	2.50	286.60
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	40/F/A/W/T	16/F/A/W/T	2.50	287.20
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	45/F/A/W/T	15/F/A/W/T	3.00	268.00
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	40/F/A/W/T	18/F/A/W/T	2.22	311.50
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	11/F/A/W/T	3.64	224.40
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	40/F/A/W/T	17/F/A/W/T	2.35	299.40
	METHA, capped	--[a]	--[a]	--[a]	--[a]
T16C	WESDEF 'expert'	40/F/A/W/T	50/F/A/W/T	0.80	711.40
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	40/F/A/W/T	50/F/A/W/T	0.80	711.40
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	40/F/A/W/T	50/F/A/W/T	0.80	711.40
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	40/F/A/W/T	53/F/A/W/T	0.75	739.40
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	40/F/A/W/T	32/F/A/W/T	1.25	476.40
	BAKFAA 'typical seed,' capped	40/F/A/W/T	32/F/A/W/T	1.25	482.70
	ELMOD6 mean	45/F/B/W/T	57/F/B/W/T	0.79	716.00
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	45/F/B/W/T	54/F/B/W/T	0.83	687.90

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	39/F/A/W/T	1.03	569.80
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	40/F/A/W/T	48/F/A/W/T	0.83	685.90
	METHA, capped	--[a]	--[a]	--[a]	--[a]
T07C	WESDEF 'expert'	40/F/A/W/T	91/F/A/W/T	0.44	1,218.90
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	40/F/A/W/T	91/F/A/W/T	0.44	1,218.90
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	40/F/A/W/T	91/F/A/W/T	0.44	1,212.10
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	40/F/A/W/T	98/F/A/W/T	0.41	1,309.50
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	40/F/A/W/T	97/F/A/W/T	0.41	1,289.00
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	40/F/A/W/T	120/F/A/W/T	0.33	1,576.60
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	40/F/A/W/T	122/F/A/W/T	0.33	1,601.40
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	207/F/A/W/T	0.19	2,666.80
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	40/F/A/W/T	84/F/A/W/T	0.48	1,136.50
	METHA, capped	--[a]	--[a]	--[a]	--[a]
Biggs AAF					
T20B	WESDEF 'expert'	40/F/A/W/T	25/F/A/W/T	1.60	401.00
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	40/F/A/W/T	21/F/A/W/T	0.95	349.80
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	40/F/A/W/T	26/F/A/W/T	1.54	402.10
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	40/F/A/W/T	25/F/A/W/T	1.60	395.90
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	40/F/A/W/T	25/F/A/W/T	1.60	396.40
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	ELMOD6 mean	40/F/A/W/T	24/F/A/W/T	1.67	378.70
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	40/F/A/W/T	29/F/A/W/T	1.38	440.30
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	30/F/A/W/T	1.33	452.40
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	40/F/A/W/T	28/F/A/W/T	1.43	430.00
	METHA, capped	--[a]	--[a]	--[a]	--[a]
Wheeler Sack AAF					
R11A	WESDEF 'expert'	45/F/B/W/T	59/F/B/W/T	0.76	740.20
	WESDEF 'expert,' capped	45/F/B/W/T	45/F/B/W/T	1.00	586.70
	WESDEF inside limits	45/F/B/W/T	58/F/B/W/T	0.78	727.50
	WESDEF inside limits, capped	45/F/B/W/T	44/F/B/W/T	1.02	577.20
	WESDEF outside limits	45/F/B/W/T	54/F/B/W/T	0.83	689.30
	WESDEF outside limits, capped	45/F/B/W/T	43/F/B/W/T	1.05	564.80
	BAKFAA 'expert seed'	45/F/B/W/T	58/F/B/W/T	0.78	727.00
	BAKFAA 'expert seed,' capped	45/F/B/W/T	43/F/B/W/T	1.05	570.50
	BAKFAA 'typical seed'	45/F/B/W/T	57/F/B/W/T	0.79	726.00
	BAKFAA 'typical seed,' capped	45/F/B/W/T	43/F/B/W/T	1.05	570.10
	ELMOD6 mean	45/F/B/W/T	48/F/B/W/T	0.94	619.00
	ELMOD6 mean, capped	45/F/B/W/T	42/F/B/W/T	1.07	562.20
	ELMOD6 'representative basin'	40/F/A/W/T	41/F/A/W/T	0.98	594.80
	ELMOD6 'representative basin,' capped	40/F/A/W/T	40/F/A/W/T	1.00	585.80
	ELMOD6 'LET'	40/F/A/W/T	35/F/A/W/T	1.14	519.10
	ELMOD6 'LET,' capped	40/F/A/W/T	36/F/A/W/T	1.11	532.80
	METHA	45/F/B/W/T	59/F/B/W/T	0.76	743.40
	METHA, capped	45/F/B/W/T	46/F/B/W/T	0.98	600.80
T02A	WESDEF 'expert'	40/F/A/W/T	47/F/A/W/T	0.85	675.30
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	45/F/B/W/T	48/F/B/W/T	0.94	625.00
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	40/F/A/W/T	47/F/A/W/T	0.85	675.40
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	40/F/A/W/T	48/F/A/W/T	0.83	684.70

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	40/F/A/W/T	48/F/A/W/T	0.83	684.60
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	40/F/A/W/T	47/F/A/W/T	0.85	666.80
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	40/F/A/W/T	45/F/A/W/T	0.89	643.20
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	38/F/A/W/T	1.05	563.20
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	40/F/A/W/T	51/F/A/W/T	0.78	717.00
	METHA, capped	--[a]	--[a]	--[a]	--[a]
T21B	WESDEF 'expert'	45/F/B/W/T	41/F/B/W/T	1.10	549.30
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	45/F/B/W/T	41/F/B/W/T	1.10	549.20
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	40/F/A/W/T	40/F/A/W/T	1.00	581.40
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	45/F/B/W/T	42/F/B/W/T	1.07	556.40
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	45/F/B/W/T	42/F/B/W/T	1.07	556.30
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	40/F/A/W/T	39/F/A/W/T	1.03	574.80
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	40/F/A/W/T	41/F/A/W/T	0.98	588.80
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	47/F/A/W/T	0.85	666.80
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	45/F/B/W/T	42/F/B/W/T	1.07	552.90
	METHA, capped	--[a]	--[a]	--[a]	--[a]

[a] Surface modulus below surface modulus threshold; therefore, the backcalculated modulus was used and not capped.

6.2.3 Composite pavements

As shown in Table 37, for the composite pavements, generally, the sections analyzed as rigid pavements (equivalent thickness method) had lower allowable loads than those sections analyzed as flexible pavements. Exceptions included Phillips R11A and R15A and Pope A16B2, where higher allowable loads were obtained when using the equivalent thickness moduli while analyzing the pavements as rigid, highlighting the importance of analyzing the sections as both flexible and rigid pavements to determine the highest allowable load. As mentioned in Chapter 5, the PCC base slab moduli were backcalculated in two ways in WESDEF. The first was to assume the PCC base slabs had deteriorated to the point that they would act like a high-quality stabilized base, and thus the moduli were backcalculated assuming the PCC base was a high-quality stabilized base. The second method used the PCC base slab option for backcalculation that generally resulted in a higher base modulus for each section. When these “with PCC as base” moduli were used for analysis, higher allowable loads were obtained during analysis. ELMOD6 moduli resulted in lower allowable loads for many of the pavement sections. However, when the surface moduli were capped for the flexible layers, overall, the allowable loads and ACN/PCN results were similar for all the programs. Additionally, the ACN/PCN results for WESDEF expert and inexperienced user results were similar. This indicates that an inexperienced user will potentially obtain similar structural evaluation results using PCASE even without manipulating the seed moduli. Additional analyses of more sections are required to confirm these preliminary conclusions, particularly since ELMOD6 results for the three composite sections from A511 could not be obtained due to a compatibility issue between the HWD files and this program.

Table 37. Structural evaluation results for composite sections.

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
Pope Field					
A14B	WESDEF 'expert'	45/F/B/W/T	87/F/B/W/T	0.52	1052.30
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	45/F/B/W/T	86/F/B/W/T	0.52	1033.80
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	45/F/B/W/T	84/F/B/W/T	0.54	1020.10
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'expert seed'	45/F/B/W/T	79/F/B/W/T	0.57	963.10
	BAKFAA 'expert seed,' capped	45/F/B/W/T	73/F/B/W/T	0.62	900.10
	BAKFAA 'typical seed'	45/F/B/W/T	79/F/B/W/T	0.57	961.70
	BAKFAA 'typical seed,' capped	45/F/B/W/T	73/F/B/W/T	0.62	897.40
	ELMOD6 mean	45/F/B/W/T	65/F/B/W/T	0.69	808.40
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'representative basin'	53/F/C/W/T	73/F/C/W/T	0.73	764.60
	ELMOD6 'representative basin,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'LET'	40/F/A/W/T	77/F/A/C/T	0.52	1045.30
	ELMOD6 'LET,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	45/F/B/W/T	82/F/B/W/T	0.55	991.10
	METHA, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF 'expert' with PCC as base	45/F/B/W/T	112/F/B/W/T	0.40	1318.30
	WESDEF 'expert' with PCC as base, capped	45/F/B/W/T	108/F/B/W/T	0.42	1277.90
	WESDEF inside limits with PCC as base	45/F/B/W/T	85/F/B/W/T	0.53	1025.20
	WESDEF inside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits with PCC as base	45/F/B/W/T	107/F/B/W/T	0.42	1271.30
	WESDEF outside limits with PCC as base, capped	45/F/B/W/T	101/F/B/W/T	0.45	1203.60
	Equivalent thickness	54/R/C/W/T	21/R/C/W/T	2.57	279.60
	Equivalent thickness, capped	54/R/C/W/T	22/R/C/W/T	2.45	285.40
A16B1	WESDEF 'expert'	40/F/A/W/T	83/F/A/W/T	0.48	1120.5
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	40/F/A/W/T	83/F/A/W/T	0.48	1112.4
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	40/F/A/W/T	82/F/A/W/T	0.49	1101.9
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	40/F/A/W/T	84/F/A/W/T	0.48	1134.30

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	40/F/A/W/T	75/F/A/W/T	0.53	1020.90
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	45/F/B/W/T	68/F/B/W/T	0.66	838.50
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'no seed values'	53/F/C/W/T	84/F/C/W/T	0.63	865.50
	ELMOD6 'no seed values,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'with seed values'	45/F/B/W/T	31/F/B/W/T	1.45	436.10
	ELMOD6 'with seed values,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	40/F/A/W/T	87/F/A/W/T	0.46	1165.20
	METHA, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF 'expert' with PCC as base	40/F/A/W/T	87/F/A/W/T	0.46	1165.3
	WESDEF 'expert' with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits with PCC as base	40/F/A/W/T	87/F/A/W/T	0.46	1165.70
	WESDEF inside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits with PCC as base	45/F/B/W/T	93/F/B/W/T	0.48	1109.20
	WESDEF outside limits with PCC as base, capped	45/F/B/W/T	89/F/B/W/T	0.51	1070.30
	Equivalent thickness	54/R/C/W/T	20/R/C/W/T	2.70	269.90
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]
A16B2	WESDEF 'expert'	45/F/B/W/T	30/F/B/W/T	1.50	420.90
	WESDEF 'expert,' capped	45/F/B/W/T	28/F/B/W/T	1.61	400.10
	WESDEF inside limits	45/F/B/W/T	37/F/B/W/T	1.22	502.00
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	45/F/B/W/T	30/F/B/W/T	1.50	420.90
	WESDEF outside limits, capped	45/F/B/W/T	28/F/B/W/T	1.61	400.10
	BAKFAA 'expert seed'	45/F/B/W/T	33/F/B/W/T	1.36	456.80
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'typical seed'	45/F/B/W/T	32/F/B/W/T	1.41	449.80
	BAKFAA 'typical seed,' capped	45/F/B/W/T	32/F/B/W/T	1.41	443.50
	ELMOD6 mean	53/F/C/W/T	42/F/C/W/T	1.26	481.80
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'no seed values'	45/F/B/W/T	38/F/B/W/T	1.18	516.60
	ELMOD6 'no seed values,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'with seed values'	40/F/A/W/T	46/F/A/W/T	0.87	657.60
	ELMOD6 'with seed values,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	45/F/B/W/T	26/F/B/W/T	1.73	386.60
	METHA, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF 'expert' with PCC as base	45/F/B/W/T	40/F/B/W/T	1.13	533.00
	WESDEF 'expert' with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits with PCC as base	45/F/B/W/T	56/F/B/W/T	0.80	708.70
	WESDEF inside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits with PCC as base	45/F/B/W/T	40/F/B/W/T	1.13	533.10
	WESDEF outside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	Equivalent thickness	50/R/B/W/T	48/R/B/W/T	1.04	565.7
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]
Campbell AAF					
R01A	WESDEF 'expert'	40/F/A/W/T	344/F/A/W/T	0.12	4377.70
	WESDEF 'expert,' capped	40/F/A/W/T	335/F/A/W/T	0.12	4267.20
	WESDEF inside limits	40/F/A/W/T	344/F/A/W/T	0.12	4379.80
	WESDEF inside limits, capped	40/F/A/W/T	336/F/A/W/T	0.12	4273.40
	WESDEF outside limits	40/F/A/W/T	344/F/A/W/T	0.12	4377.40
	WESDEF outside limits, capped	40/F/A/W/T	502/F/A/W/T	0.08	6348.50
	BAKFAA 'expert seed'	40/F/A/W/T	344/F/A/W/T	0.12	4376.20
	BAKFAA 'expert seed,' capped	40/F/A/W/T	335/F/A/W/T	0.12	4257.10
	BAKFAA 'typical seed'	40/F/A/W/T	344/F/A/W/T	0.12	4379.70

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'typical seed,' capped	40/F/A/W/T	335/F/A/W/T	0.12	4261.40
	ELMOD6 mean	40/F/A/W/T	413/F/A/W/T	0.10	5242.40
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'no seed values'	40/F/A/W/T	455/F/A/W/T	0.09	5763.50
	ELMOD6 'no seed values,' capped	40/F/A/W/T	444/F/A/W/T	0.09	5623.90
	ELMOD6 'with seed values'	40/F/A/W/T	127/F/A/W/T	0.31	1669.60
	ELMOD6 'with seed values,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	40/F/A/W/T	455/F/A/W/T	0.09	5763.90
	METHA, capped	40/F/A/W/T	453/F/A/W/T	0.09	5733.70
	WESDEF 'expert' with PCC as base	40/F/A/W/T	352/F/A/W/T	0.11	4475.30
	WESDEF 'expert' with PCC as base, capped	40/F/A/W/T	343/F/A/W/T	0.12	4365.50
	WESDEF inside limits with PCC as base	40/F/A/W/T	352/F/A/W/T	0.11	4476.40
	WESDEF inside limits with PCC as base, capped	40/F/A/W/T	343/F/A/W/T	0.12	4367.80
	WESDEF outside limits with PCC as base	40/F/A/W/T	352/F/A/W/T	0.11	4475.20
	WESDEF outside limits with PCC as base, capped	40/F/A/W/T	343/F/A/W/T	0.12	4365.80
	Equivalent thickness	50/R/B/W/T	110/R/B/W/T	0.45	1306.90
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]
Phillips AAF					
R11A	WESDEF 'expert'	45/F/B/W/T	17/F/B/W/T	2.65	285.70
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	45/F/B/W/T	27/F/B/W/T	1.67	389.90
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	45/F/B/W/T	23/F/B/W/T	1.96	354.20
	WESDEF outside limits, capped	45/F/B/W/T	22/F/B/W/T	2.05	337.40
	BAKFAA 'expert seed'	45/F/B/W/T	13/F/B/W/T	3.46	243.00
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	45/F/B/W/T	30/F/B/W/T	1.50	423.40

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	53/F/C/W/T	13/F/B/W/T	4.08	229.80
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'no seed values'	--[b]	--[b]	--[b]	--[b]
	ELMOD6 'no seed values,' capped	--[b]	--[b]	--[b]	--[b]
	ELMOD6 'with seed values'	40/F/A/W/T	17/F/A/W/T	2.35	299.80
	ELMOD6 'with seed values,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	45/F/B/W/T	33/F/B/W/T	1.36	460.80
	METHA, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF 'expert' with PCC as base	45/F/B/W/T	28/F/B/W/T	1.61	403.10
	WESDEF 'expert' with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits with PCC as base	70/F/D/W/T	8/F/D/W/T	8.75	169.20
	WESDEF inside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits with PCC as base	70/F/D/W/T	8/F/D/W/T	8.75	169.20
	WESDEF outside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	Equivalent thickness	54/R/C/W/T	57/R/C/W/T	0.95	617.30
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]
R09A	WESDEF 'expert'	53/F/C/W/T	17/F/C/W/T	3.12	259.80
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	53/F/C/W/T	24/F/C/W/T	2.21	326.60
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	53/F/C/W/T	31/F/C/W/T	1.71	385.10
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	53/F/C/W/T	21/F/C/W/T	2.52	296.60
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	53/F/C/W/T	17/F/C/W/T	3.12	258.20
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	ELMOD6 mean	70/F/D/W/T	5/F/D/W/T	14.00	148.60
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 'no seed values'	--[b]	--[b]	--[b]	--[b]
	ELMOD6 'no seed values,' capped	--[b]	--[b]	--[b]	--[b]
	ELMOD6 'with seed values'	53/F/C/W/T	5/F/C/W/T	10.60	150.30
	ELMOD6 'with seed values,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	53/F/C/W/T	9/F/C/W/T	5.89	193.20
	METHA, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF 'expert' with PCC as base	53/F/C/W/T	33/F/C/W/T	1.61	403.00
	WESDEF 'expert' with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits with PCC as base	53/F/C/W/T	38/F/C/W/T	1.39	452.00
	WESDEF inside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits with PCC as base	54/R/C/W/T	29/R/C/W/T	1.86	349.40
	WESDEF outside limits with PCC as base, capped	53/F/C/W/T	38/F/C/W/T	1.39	452.00
	Equivalent thickness	54/R/C/W/T	31/R/C/W/T	1.74	372.7
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]
R15A	WESDEF 'expert'	45/F/B/W/T	13/F/B/W/T	3.46	245.30
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	45/F/B/W/T	12/F/B/W/T	3.75	232.00
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	45/F/B/W/T	8/F/B/W/T	5.63	191.30
	WESDEF outside limits, capped	45/F/B/W/T	10/F/B/W/T	4.50	207.20
	BAKFAA 'expert seed'	45/F/B/W/T	15/F/B/W/T	3.00	262.60
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	45/F/B/W/T	15/F/B/W/T	3.00	262.80
	BAKFAA 'typical seed,' capped	--[a]	--[a]	--[a]	--[a]
	ELMOD6 mean	53/F/C/W/T	13/F/C/W/T	4.08	221.80
	ELMOD6 mean, capped	--[a]	--[a]	--[a]	--[a]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	ELMOD6 'no seed values'	--[b]	--[b]	--[b]	--[b]
	ELMOD6 'no seed values,' capped	--[b]	--[b]	--[b]	--[b]
	ELMOD6 'with seed values'	45/F/B/W/T	17/F/B/W/T	2.65	280.50
	ELMOD6 'with seed values,' capped	--[a]	--[a]	--[a]	--[a]
	METHA	45/F/B/W/T	11/F/B/W/T	4.09	220.20
	METHA, capped	45/F/B/W/T	14/F/B/W/T	3.21	246.50
	WESDEF 'expert' with PCC as base	45/F/B/W/T	17/F/B/W/T	2.65	279.90
	WESDEF 'expert' with PCC as base, capped	45/F/B/W/T	14/F/B/W/T	3.21	248.60
	WESDEF inside limits with PCC as base	45/F/B/W/T	5/F/B/W/T	9.00	158.80
	WESDEF inside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits with PCC as base	45/F/B/W/T	5/F/B/W/T	9.00	158.80
	WESDEF outside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	Equivalent thickness	54/R/C/W/T	53/R/C/W/T	1.02	575.80
	Equivalent thickness capped	--[a]	--[a]	--[a]	--[a]
A511					
A05B	WESDEF 'expert'	45/F/B/W/T	134/F/B/W/T	0.34	1564.70
	WESDEF 'expert,' capped	45/F/B/W/T	129/F/B/W/T	0.35	1503.10
	WESDEF inside limits	45/F/B/W/T	172/F/B/W/T	0.26	1974.10
	WESDEF inside limits, capped	45/F/B/W/T	170/F/B/W/T	0.26	1955.50
	WESDEF outside limits	45/F/B/W/T	134/F/B/W/T	0.34	1564.70
	WESDEF outside limits, capped	45/F/B/W/T	129/F/B/W/T	0.35	1503.10
	BAKFAA 'expert seed'	45/F/B/W/T	195/F/B/W/T	0.23	2226.90
	BAKFAA 'expert seed,' capped	45/F/B/W/T	181/F/B/W/T	0.25	2076.90
	BAKFAA 'typical seed'	45/F/B/W/T	178/F/B/W/T	0.25	2043.30
	BAKFAA 'typical seed,' capped	45/F/B/W/T	122/F/B/W/T	0.37	1428.90

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	ELMOD6 mean	--[c]	--[c]	--[c]	--[c]
	ELMOD6 mean, capped	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'no seed values'	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'no seed values,' capped	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'with seed values'	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'with seed values,' capped	--[c]	--[c]	--[c]	--[c]
	METHA	45/F/B/W/T	176/F/B/W/T	0.26	2023.70
	METHA, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF 'expert' with PCC as base	45/F/B/W/T	175/F/B/W/T	0.26	2012.40
	WESDEF 'expert' with PCC as base, capped	45/F/B/W/T	174/F/B/W/T	0.26	1996.00
	WESDEF inside limits with PCC as base	40/F/A/W/T	152/F/A/W/T	0.26	1977.00
	WESDEF inside limits with PCC as base, capped	40/F/A/W/T	149/F/A/W/T	0.27	1946.90
	WESDEF outside limits with PCC as base	45/F/B/W/T	135/F/B/W/T	0.33	1571.50
	WESDEF outside limits with PCC as base, capped	45/F/B/W/T	129/F/B/W/T	0.35	1510.20
	Equivalent thickness	54/R/C/W/T	30/R/C/W/T	1.80	356.30
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]
A15B	WESDEF 'expert'	53/F/C/W/T	90/F/C/W/T	0.59	913.40
	WESDEF 'expert,' capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits	53/F/C/W/T	90/F/C/W/T	0.59	913.40
	WESDEF inside limits, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits	53/F/C/W/T	91/F/C/W/T	0.58	920.60
	WESDEF outside limits, capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'expert seed'	53/F/C/W/T	87/F/C/W/T	0.61	890.80
	BAKFAA 'expert seed,' capped	--[a]	--[a]	--[a]	--[a]
	BAKFAA 'typical seed'	53/F/C/W/T	82/F/C/W/T	0.65	842.30
	BAKFAA 'typical seed,' capped	53/F/C/W/T	80/F/C/W/T	0.66	823.60
	ELMOD6 mean	--[c]	--[c]	--[c]	--[c]
	ELMOD6 mean, capped	--[c]	--[c]	--[c]	--[c]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	ELMOD6 'no seed values'	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'no seed values,' capped	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'with seed values'	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'with seed values,' capped	--[c]	--[c]	--[c]	--[c]
	METHA	53/F/C/W/T	88/F/C/W/T	0.60	897.10
	METHA, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF 'expert' with PCC as base	53/F/C/W/T	91/F/C/W/T	0.58	921.10
	WESDEF 'expert' with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF inside limits with PCC as base	53/F/C/W/T	91/F/C/W/T	0.58	921.10
	WESDEF inside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	WESDEF outside limits with PCC as base	53/F/C/W/T	91/F/C/W/T	0.58	921.00
	WESDEF outside limits with PCC as base, capped	--[a]	--[a]	--[a]	--[a]
	Equivalent thickness	54/R/C/W/T	24/R/C/W/T	2.25	299.20
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]
T09B	WESDEF 'expert'	45/F/B/W/T	76/F/B/W/T	0.59	924.80
	WESDEF 'expert,' capped	45/F/B/W/T	56/F/B/W/T	0.80	709.50
	WESDEF inside limits	45/F/B/W/T	87/F/B/W/T	0.52	1051.90
	WESDEF inside limits, capped	45/F/B/W/T	78/F/B/W/T	0.58	948.80
	WESDEF outside limits	45/F/B/W/T	76/F/B/W/T	0.59	924.80
	WESDEF outside limits, capped	45/F/B/W/T	56/F/B/W/T	0.80	709.50
	BAKFAA 'expert seed'	45/F/B/W/T	87/F/B/W/T	0.52	1047.60
	BAKFAA 'expert seed,' capped	45/F/B/W/T	77/F/B/W/T	0.58	941.30
	BAKFAA 'typical seed'	45/F/B/W/T	85/F/B/W/T	0.53	1022.60
	BAKFAA 'typical seed,' capped	45/F/B/W/T	72/F/B/W/T	0.63	884.90
	ELMOD6 mean	--[c]	--[c]	--[c]	--[c]
	ELMOD6 mean, capped	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'no seed values'	--[c]	--[c]	--[c]	--[c]

Section	Moduli Used	ACN	PCN	ACN/PCN	Allowable Load, kips
	ELMOD6 'no seed values,' capped	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'with seed values'	--[c]	--[c]	--[c]	--[c]
	ELMOD6 'with seed values,' capped	--[c]	--[c]	--[c]	--[c]
	METHA	45/F/B/W/T	82/F/B/W/T	0.55	992.80
	METHA, capped	45/F/B/W/T	66/F/B/W/T	0.68	818.80
	WESDEF 'expert' with PCC as base	45/F/B/W/T	90/F/B/W/T	0.50	1075.80
	WESDEF 'expert' with PCC as base, capped	45/F/B/W/T	80/F/B/W/T	0.56	969.90
	WESDEF inside limits with PCC as base	45/F/B/W/T	91/F/B/W/T	0.49	1086.50
	WESDEF inside limits with PCC as base, capped	45/F/B/W/T	83/F/B/W/T	0.54	1000.00
	WESDEF outside limits with PCC as base	45/F/B/W/T	91/F/B/W/T	0.49	1087.00
	WESDEF outside limits with PCC as base, capped	45/F/B/W/T	83/F/B/W/T	0.54	1001.50
	Equivalent thickness	54/R/C/W/T	23/R/C/W/T	2.35	295.5
	Equivalent thickness, capped	--[a]	--[a]	--[a]	--[a]

[a] Surface modulus below surface modulus threshold; therefore, the backcalculated modulus was used and not capped.

[b] Surface modulus was fixed for WESDEF; therefore, no representative basin was selected.

[c] HWD file was incompatible with ELMOD6.

7 Conclusions and Recommendations

During the research period, the current USAF airfield pavement analysis procedure, including the processes used for backcalculating layer moduli, was reviewed and compared to processes utilized by other transportation agencies and those proposed by academia. Airfield deflection data were then analyzed using various software and backcalculation procedures to provide recommendations for improving both the software and processes used by the USAF in evaluating the structural capacity of airfield pavement assets. Conclusions and recommendations are presented in the following sections.

7.1 Conclusions

- The procedures for backcalculation and structural analysis vary between the Services, and the exact methods used by each are not well documented.
- Using either the current USAF or Army backcalculation procedure produces reasonable backcalculated modulus results for AC and PCC pavements and, in some cases, for composite pavements.
- The most difficult pavement type to backcalculate is an AC/PCC composite pavement regardless of method or software program used.
- The Army method of modifying moduli to obtain acceptable backcalculated moduli produces similar results to those obtained using the USAF procedure when allowed to conduct the backcalculating analyses outside the preset moduli limits.
- With the exception of the composite pavements, an inexperienced user will obtain reasonable modulus results using either WESDEF or BAKFAA.
- BAKFAA produced similar backcalculated moduli to those obtained with WESDEF using expert or inexperienced methods.
- ELMOD6 did not produce similar backcalculated moduli results to those obtained using WESDEF and produced more unreasonable modulus values than the other programs. The ELMOD6 program predicted higher moduli for the subgrades of many of the sections analyzed.
- The current USAF practice of capping the surface moduli results in similar ACN/PCN ratios and allowable loads for PCC and AC pavements regardless of using an expert or inexperienced user method in WESDEF. Additionally, similar ACN/PCN ratios and allowable loads

to those obtained in WESDEF were found when using BAKFAA moduli (either expert or default seed moduli).

- Backcalculating and evaluating composite pavements are difficult procedures for both experienced and inexperienced users. Additional guidance is required to make recommendations for improving the accuracy or reasonableness of composite pavement results.
- The forwardcalculation subgrade moduli correlated well to the backcalculated subgrade moduli, and the process was an easy check for reasonableness of subgrade results when conducting backcalculation. This approach was best applied to subgrade comparisons, and intermediate layers moduli should not be used at this time.
- The METHA approach provided a reasonably fast method of determining whether subgrade moduli are reasonable and can easily be used in WESDEF. This test could be used by inexperienced users to check their subgrade moduli prior to accepting backcalculation results.
- The benchmarking approach may also be useful for identifying weak areas in an AC pavement feature if applied to every station where HWD data are collected. Based on these preliminary results, this method could be applied as a check for backcalculated moduli and/or for identifying weak spots in each pavement feature or to determine whether the station selected as the representative basin is truly representative of the moduli for all pavement layers. For now, this approach can be applied only for AC pavements.

7.2 Recommendations

- It is recommended that the USAF continue using WESDEF for backcalculation, employing a modified procedure described at the end of this chapter.
- The data set used in this report should be expanded to include additional pavement sections including USAF pavement sections to identify limitations to the current backcalculation process, such as thin AC pavements and strong bases such as macadam, stabilized, or rubblized PCC not covered in this report.
- Following the review of the other agencies' backcalculation procedures, the following areas should be considered in future projects:
    - Methods for backcalculating highly-distressed AC pavements
    - Methods for backcalculating AC pavements with significant debonding or delamination between adjacent AC layers

    - Impact of backcalculated results using HWD data collected when the temperature is above 90°F for AC pavements or 85°F for PCC pavements and determination of a single temperature cutoff for both pavement types
    - Evaluation of saturated soils using a stiff layer
    - Evaluation of thin stabilized layers beneath PCC surfaces
    - Effect of small PCC slab size on HWD deflection basins

- The percent error for the backcalculation results should be moved to the main backcalculation screen in PCASE. If the percent errors are over 4 percent, the pavement structure should be modified to determine whether fewer or additional layers produce reasonable results with a lower percent error.
- The use of RMS error is recommended for future versions of PCASE to be consistent with other backcalculation programs.
- This study focused primarily on multilayer linear elastic analysis; it is recommended that nonlinear stress-dependent, genetic algorithm, and 3-D finite element backcalculation approaches be considered in future research efforts.
- The current PCASE implementation of selecting the representative basin should be reexamined to match the recommended approach described in UFC 03-260-03 (2001).
- Additional research into composite pavement backcalculation and evaluation methods is recommended.
- Use of the METHA method and/or the forwardcalculation process as a check of reasonableness for subgrade moduli for inexperienced users is recommended.
- Additional research to develop guidance for using the benchmarking method for PCC and composite pavements and to determine whether the AC benchmark ranges extrapolated from truck traffic are representative of airfield pavements is recommended. This research may lead to an easy method to identify or confirm weak or troubled areas in pavements that need additional tests (such as DCP) or determine whether data points need to be eliminated from deflection basins for backcalculation.
- Additional research is recommended to determine how RMS error can be used to determine the reasonableness or accuracy of moduli. RMS error reported in either percent or mils is used by other programs using deflections. Additional research into the most appropriate approach is recommended.

- Finally, additional research on determining seed values, moduli ranges, and Poisson's ratio values as a function of temperature and age is recommended.

7.3 Recommended USAF pavement evaluation process

Based on the results of this research effort, a revised USAF procedure is recommended for evaluating pavements and is presented in Appendix A.

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Appendix A

A.1 Pre-evaluation preparations

- Research previous structural evaluation data and PCI (old reports)
  - What type of structural analysis was conducted [i.e., layered elastic analysis (LEEP) or airfield pavement evaluation (APE)]?
  - If not LEEP, why?
  - How many evaluations have been conducted on this airfield previously?
  - Is there old pit data available?
  - Do many sections have restricted allowable loads/PCNs?
  - What is the overall condition of the pavement sections including distress types, severity levels, and extents?
  - Review and compare last PCI to last structural evaluation drawings to determine whether any discrepancies between pavement condition and structural capacity exist.
- Obtain current data from base
  - Common installation picture
  - Imagery
  - As-built drawings for construction since last evaluation including overlay, maintenance, and rehabilitation records
  - Utility drawings to develop preliminary test plan
  - Traffic data – specific data on type and number of aircraft operations
- Prepare preliminary drawings
- Prepare PAVER/PCASE database and update construction history in PAVER
  - Prepare a draft database or use recent PAVER database and update information including facilities, branches, and sections.
  - Input layer structures and previous HWD data for each pavement section.
  - Update default settings as required.
- Generate PCI inspection sheets
  - Use last PCI database to identify sample units to be inspected.

- Check equipment
    - Core drill
    - DCP
    - HWD
        - Conducted on test slab.
        - Ensure default settings are correct.
        - Ensure HWD operator has map for HWD locations.
    - PSPA – ensure that the PSPA is calibrated- conducted on test slab.
    - Other equipment such as GPR or MIRA, if necessary
- Coordinate with installation
    - Evaluation dates
    - NOTAM closures
    - Work clearance
    - Entry authorization letter
    - Photo clearance letter

A.2 Onsite evaluation

- In-brief installation personnel
    - Complete any base coordination items and obtain missing data.
    - Obtain climate data (5-day min/max air temps for asphalt analysis).
    - Do airfield driving local conditions familiarization/paper work.
    - Identify any issues with draft test plans – pavement segmentation and type.
    - Identify overall visual condition.
    - Identify specific base problems/concerns.
    - Discuss causes of distresses, traffic, and drainage.
- Perform testing
    - Conduct pavement condition survey (PCI).
        - Collect photos, record photos in log, and identify distress types and severity for each photo.
        - Note any needed changes to the airfield drawings.
    - Conduct HWD testing
        - Ensure defaults are set properly - 12-in. plate and sensors at 12-in. spacing.
        - Conduct a minimum of 5 tests per pavement section.

- Create separate HWD test file for each section – use temporary name if needed.
- Manually input test location number – unique number for each test point.
- If you start a file, close it. If you need to do additional testing, you will need to combine files using a text editor.
- Test at center of PCC slabs.
- Use the current drop sequence: 2-4-4 for PCC and 1-2-2 for AC.
- Test at 100-ft intervals on alternating sides of center line in wheel paths.
- Test on 100- to 300-ft grid on aprons.
- Collect surface temperature for AC.
- Reject any data that has errors (e.g., deflections not decreasing).
- Monitor HWD data acquisition screens to observe patterns in results.
- Determine whether there are new section breaks/ additional core/ DCP requirements.
- If conditions (long stretches of linear segmentation) warrant, test PCC joints.
  - ➢ Test longitudinal and transverse at every 5th location
  - ➢ May need a reference slab to check every 1 to 2 hr

- o Conduct coring operations
  - Number of cores based on number of previous cores/pits and size of section.
  - Core through high-quality stabilized base.
  - Measure thickness to layer breaks.
  - Obtain soil sample if never sampled before or if core does not agree with previous data.
  - Record thorough notes on core log regarding cores, soil type and color, and thicknesses.
- o Complete DCP tests
  - Begin DCP test at top of base layer.
  - Core/drill through if refusal occurs.
  - Auger through stabilized bases if you get DCP refusal.
  - After conducting a DCP test, auger out core hole to get field classification of soil type.

    - Complete PSPA tests
        - Test at center of PCC slabs - set sensor spacing based on pavement thickness.
        - Test at 100- to 300-ft intervals on alternating sides of center line in the wheel paths.
        - Record surface temperature for AC.

A.3 Field data consolidation and analysis

- Manage data
    - Back up all files to external drive/disk daily.
    - Review and consolidate all data daily.
    - Establish/revise test plan for following day.
- Manage PCI data
    - Collect PCI data.
    - Determine PCI using PAVER.
- Manage HWD data
    - Rename filenames as required.
    - Select representative basin at end of each day.
    - Look for variability (stiff/weak areas) to determine whether sections need to be broken.
    - Look at DCPs/cores to reconcile issues with section breaks.
    - Determine whether there are additional core/DCP requirements.
- Manage core log data
    - Review core log data for adequacy of information and problem areas.
    - Calculate average core thickness from old and new data and enter into database. (Cap individual core flexural strength at 850 psi.)
    - Compute an average flexural strength of all past and current cores. (Cap average at 800 psi.)
    - If no core data are collected or available, assume 700 psi for pavements in the U.S. and 600 psi for those outside the U.S. or of uncertain quality.
- Manage DCP data
    - Input or upload DCP data into PCASE.
    - Use DCP software to break pavement into layers.
    - Build layer descriptions in using core log.

    - Print DCP plots if printer is available and time permits.
    - Enter layer thickness and CBR/K values into database.

- Manage PSPA data

    - Calculate flex strength and compare with past split tensile flex strength.
    - Enter average flex data into database.

- Update drawings

    - Facility map
    - Branch and section map
    - Pavement rank map (with section bubbles)
    - PCI map (with section bubbles)
    - Core test location map
    - HWD test location map
    - PSPA test location map

- Inventory and group soils

A.4 Backcalculate layer moduli

- Make changes to HWD data file names if required.
- Merge HWD data files in text editor if required.
- Import HWD data files into current PAVER file.
- Review impulse stiffness modulus (ISM) plots.

    - Look for variability (stiff/weak areas) to determine whether sections need to be broken.
    - Look at DCPs/cores to reconcile issues with section breaks.
    - Select basins for inclusion in analysis.

        - Remove high values.
        - Verify low values.

- Update or enter pavement structure model into WESDEF layer grid based on measured thicknesses and/or DCP data.

    - Backcalculating in WESDEF for PCC pavements.

        - If core/DCP testing shows slab on subgrade, use a two-layer model.
        - If core/DCP testing shows base and/or subbase is present, use a three-layer model.
        - Combine strong base/subbase layers and/or combine weaker subbase/subgrade layers.

      - Backcalculate all layers during the initial analysis.
        - ➢ Examine the backcalculated moduli results for each station and their percent errors.
        - ➢ Determine whether the moduli are reasonable compared to the modulus limits presented in Chapter 5.
        - ➢ If necessary, compare the backcalculated subgrade moduli to those obtained using the Metha method or forwardcalculation.
        - ➢ If reasonable, use these moduli for analysis.
      - If the results are erratic (moduli vary substantially from station to station), have high percent errors (over 4 percent), or are unreasonable (outside modulus limits for the material type), set limits to off and reanalyze.
        - ➢ Determine whether these results are more reasonable.
        - ➢ If so, use the results obtained allowing the backcalculation outside the limits for evaluation.
      - If the base layer gives erratic or unreasonable results, fix the base layer modulus using DCP data and CBR to modulus relationship (vice K to modulus).
        - ➢ Try this with limits on first and then with limits off, if needed.
        - ➢ If reasonable, use these moduli for analyses.
      - If the results are still erratic, unreasonable, or errors are still high, try a two-layer model with limits on first, then limits off if needed.
        - ➢ Determine whether these moduli are more reasonable.
        - ➢ Check backcalculated subgrade modulus to that obtained using DCP or from Metha or forwardcalculation approaches.
        - ➢ If reasonable, use these moduli for analyses.
    - o Backcalculating in WESDEF for AC pavements (>3.0 in. AC surface)
      - Use a three-layer model to start.
      - Combine strong base/subbase layers and/or combine weaker subbase/subgrade layers.
      - Backcalculate all layers in the initial analysis with limits on.

    - Examine the backcalculated moduli results for each station and their percent errors.
    - Determine whether the moduli are reasonable compared to the modulus limits presented in Chapter 5.
    - If necessary, compare the backcalculated subgrade moduli to those obtained using the Metha method or forwardcalculation.
    - If reasonable, use these moduli for analysis.

  - If the results are erratic (moduli vary substantially from station to station), have high percent errors (over 4 percent), or are unreasonable (outside modulus limits for the material type), set the limits to off and conduct the analysis again.

    - Determine whether these results are more reasonable.
    - If so, use the results obtained allowing the backcalculation outside the limits for evaluation.

  - If the base layer gives erratic or unreasonable results, fix the base layer modulus using DCP data and CBR to modulus relationship (vice K to modulus).

    - Try this with limits on first and then with limits off, if needed.
    - If reasonable, use these moduli for analysis.

  - If the results are still erratic, unreasonable, or errors are still high, try a four-layer model with limits on first, then limits off if needed.

    - Determine whether these moduli are more reasonable.
    - Check the backcalculated subgrade modulus to that obtained using DCP or from Metha or forwardcalculation approaches.
    - If reasonable, use these moduli for analyses.

- NOTE: If the subgrade modulus values appear to be unreasonably high (> 30,000 psi), look at the depth to bedrock (DTB). For an AC pavement, PCASE has a routine that will calculate the DTB. If there appears to be a DTB issue with PCC, use the AC DTB routine for a nearby AC section and use the DTB value for the PCC section. Also examine borings, test pits, or other data to get an estimated DTB.
- Backcalculating in WESDEF for thin AC layers (<3 in.)

  - Follow the procedure for AC layers.

      - If unreasonable or erratic results are obtained, fix the AC modulus using the temperature/design modulus and conduct the backcalculation again.
      - Check the backcalculated subgrade value to DCP, Metha, or forwardcalculated results.
      - If reasonable, use these moduli for analyses.

  - Backcalculating in WESDEF for composite pavements (AC over PCC)

      - Use a three-layer system (AC layer>3 in., PCC base slab, and subgrade) as the first trial analyzing the system both inside and outside the limits.

        - ➢ If the modulus value for the PCC layer is high (>4,000,000 psi), the error values are low, and the other modulus results are reasonable, keep the model.

          - If the errors are high, or the modulus results are unreasonable, compute the AC and PCC layers as an equivalent thickness of PCC and perform the backcalculation analysis again.
          - Check the subgrade modulus by comparing to DCP, Metha, or forwardcalculation results.
          - If reasonable, use these moduli for analyses.

        - ➢ If the modulus values of the PCC layer are low (<4,000,000 psi) (indicating that the PCC is most likely cracked extensively), change the PCC base layer to a high-quality stabilized base, and perform the backcalculation analysis again.

          - Perform the analysis both inside and outside the limits.
          - Determine whether the modulus results are reasonable.
          - Check the subgrade modulus by comparing to DCP, Metha, or forward calculation results.
          - Chose the model that allows the highest allowable loads when evaluated for traffic (see next section for evaluation guidance).

        - ➢ If the PCC layer modulus values are very low (<2,000,000 psi), consider reanalyzing the section as a flexible section over a stabilized or unstabilized base layer in lieu of a rigid PCC base layer or high-quality stabilized base.

— Determine whether the modulus results are reasonable.
— Check the subgrade modulus by comparing to DCP, Metha, or forward calculation results.
— If reasonable, use these moduli for analyses.

➢ If the AC layer is < 3 in., transform the AC and PCC layers into a single PCC layer using the equivalent thickness equation and analyze the system both inside and outside the limits.

— Determine whether the modulus results are reasonable.
— Check the subgrade modulus by comparing to DCP, Metha, or forward calculation results.
— If reasonable, use this structure for analysis.

A.5 Using backcalculated moduli for analysis

- Generation and selection of the appropriate traffic pattern
- Evaluation of rigid pavements
  - Ensure that the flex strength measured using a PSPA or determined through splitting tensile testing of cores is entered into the PCASE layer structure.
  - If the PCC layer has a backcalculated modulus >5,000,000 psi, cap it at 5,000,000 psi for analysis.
  - If the PCC layer has a backcalculated modulus <5,000,000 psi, use the actual backcalculated modulus.
  - Conduct the analysis, and report the results.
- Evaluation of thick flexible pavements (AC layer> 3 in.)
  - If the AC pavement layer is < 4 years old and the backcalculated modulus value < 350,000 psi, use the actual backcalculated modulus; otherwise, set the modulus at 350,000 psi.
  - If the AC pavement layer is between 4 and 10 years old and the backcalculated modulus <500,000 psi, use the actual backcalculated modulus; otherwise, set the modulus to 500,000 psi.
  - If the AC pavement layer is between 10 and 20 years old and the backcalculated modulus <750,000 psi, use the actual backcalculated modulus; otherwise, set the modulus to 750,000 psi.
  - If the AC pavement layer is >20 years old and the backcalculated modulus <1,000,000 psi, use the backcalculated modulus; otherwise, set the modulus to 1,000,000 psi.
  - Conduct the analysis, and report the results.

- Evaluation of thin flexible pavements (AC layer<3 in.)
  - o Set the AC modulus to design/temperature modulus.
  - o Conduct the analysis, and report the results.
- Evaluation of composite pavements (AC/PCC)
  - o If the flexural strength of the PCC base layer is < 400 psi or the modulus of subgrade reaction (*k*) for the foundation layers beneath the PCC is > 200 pci, evaluate the pavement:
    - First as a rigid pavement (using equivalent thickness backcalculated moduli), and
    - Second as a flexible pavement (using the backcalculated moduli for each layer- capped if necessary following AC pavement evaluation directions).
    - Conduct the analysis.
    - The one with the higher allowable gross weight is then selected as the solution.
    - Report the results.
  - o If the preceding conditions do not apply, then evaluate the pavement as a rigid pavement using the backcalculated moduli based on the equivalent PCC thickness.
    - Cap the PCC modulus at 5,000,000 psi if necessary.
    - Conduct the analysis, and report the results.
  - o If the composite pavement structure is evaluated as AC over a high-quality stabilized base, stabilized base, or unstabilized base and the AC thickness is over 3 in., then use the backcalculated values for analysis.
    - Cap the AC modulus based on age following AC evaluation procedures.
  - o Conduct the analysis, and report the results. If the AC thickness is thin (<3 in.), evaluate the system as an equivalent PCC thickness and evaluate using these backcalculated values for PCC analysis. Alternatively, set the AC modulus based on temperature/design modulus.
    - Cap the surface modulus based on AC age if necessary.
    - Cap the surface modulus to 5,000,000 psi if required.
    - Conduct the analysis, and report the results.

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14. ABSTRACT
During the period October 2013 through August 2014, research was conducted at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, to improve the U.S. Air Force's (USAF's) airfield pavement structural evaluation procedures. Determining the structural integrity of airfield pavement relies on the analysis of pavement deflection data collected using the falling weight deflectometer (FWD) or heavy weight deflectometer (HWD). These deflection data are used to backcalculate pavement layer moduli, which are then used to determine the number of allowable passes and the allowable load that the pavement is able to support. The current airfield pavement analysis procedures, including the processes used for backcalculating layer moduli, were reviewed and compared to processes utilized by other transportation agencies and those proposed by academia. Airfield deflection data were then analyzed using current and proposed backcalculation procedures to provide recommendations for improving both the software and processes used by the USAF in evaluating the structural capacity of airfield pavement assets. This report summarizes the literature review, presents analyses of FWD/HWD data, and provides recommendations for improving the procedures used for backcalculation.

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